EDWARDS, RICHARD D., Ph.D. The Neurosciences and Music Education: An Online Database of Brain Imaging Neuromusical Research. (2008)
Directed by Dr. Donald A. Hodges. 162 pp.

The purpose of this study was to create an online database to organize and summarize the field of neuromusical research (i.e., the study of brain processes involved with musical experiences). The guiding principles of this dissertation were to (1) assess and clarify the current state of neuromusical research, and (2) explore how this research relates to the pedagogical, psychological and philosophical foundations of music education. Given the rise of brain-imaging neuromusical research in the last two decades, in conjunction with a lack of holistic efforts to evaluate these studies, there is a clear need to compile and summarize neuromusical research into a summative database. Until this time, no such resource has existed.

The resulting database of this project has been titled the Musical Brain Imaging Research Database (*MusicBIRD*) and currently holds 473 studies of neuromusical research available online at http://www.uncg.edu/mus/mri/neuromusical.html. Qualifying neuromusical studies were identified with a keyword search for "music" and "brain" in leading electronic research databases (e.g., PubMed and RILM). After reviewing each study, summative information was entered into an electronic storage format within the following data fields: Title, Author(s), Date, Keywords, Source, Volume, Issue, Online Source, and Abstract.

A content analysis of the studies in the final database was conducted to reveal trends in neuromusical research and insights for music educators about the role of neuroscience in music teaching. Among the leading trends in neuromusical research

identified in the content analysis were the most frequently used brain imaging devices (ERP in 27.80% and EEG in 28.57% of all *MusicBIRD* studies), and the most common research methodologies - the evaluation of changes in brain activity due to music processing (35.57% of all *MusicBIRD* studies) and comparisons between musically and non-musically trained subjects (25.57% of all *MusicBIRD* studies).

The implications of neuromusical research for music educators include a strengthening of the belief that the potential for music processing is ubiquitous to all humans, and that until more longitudinal studies can be conducted, a clear understanding of whether musical training does or does not have an effect on non-musical brain processes (e.g., language skills) is not possible at this time. Based on a review of neuromusical research through 2006, several recommendations for future research include brain imaging scans associated with effective pedagogical music learning practices, longitudinal studies of brain development during periods of musical training (e.g., preschool to adulthood), and investigating the potential for shared, proximal, or distinct neural networks dedicated to music and non-music systems.

# THE NEUROSCIENCES AND MUSIC EDUCATION:

# AN ONLINE DATABASE OF BRAIN IMAGING

# NEUROMUSICAL RESEARCH

by

Richard D. Edwards

A Dissertation Submitted to
the Faculty of The Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Greensboro
2008

Approved by

_____
Committee Chair

TABLE OF CONTENTS

Page

LIST OF TABLES ..... vi

LIST OF FIGURES ..... vii

CHAPTER

I. INTRODUCTION ..... 1

Overview of Neuroscience ..... 2
The Symbiosis of Music and Neuroscience ..... 3
A Holistic Approach For Studying Musical Processes ..... 4
The Unique Process of Human Musicality ..... 5
The Biological Value of Human Musicality ..... 8
Musical Morphology: The Effect of Music Processing On Brain Growth ..... 11
The Role of Music Processing in Learning and Memory ..... 12
The Philosophical Implications of Neuromusical Research ..... 15
Development of the Dissertation Idea ..... 18
Research Problem ..... 20
Research Purpose ..... 21
Scope of the Study ..... 22

II. A MUSICIAN'S GUIDE TO NEUROSCIENCE AND RELATED LITERATURE ..... 23

Neuroanatomy ..... 24
Hindbrain: The Brainstem and Cerebellum ..... 26
Forebrain: The Cerebral Cortex ..... 26
The Limbic System ..... 29
Brain Cells ..... 30
Neurophysiology ..... 33
The Behavioral Level ..... 35
The Systems Level ..... 37
The Networks Level ..... 38
The Cellular Level ..... 43
The Molecular (Synaptic) Level ..... 48
The Genetic Level ..... 52
Brain Imaging Technology in Neuromusical Research ..... 53
Magnetic Resonance Imaging ..... 54

Functional Magnetic Resonance Imaging ..... 55
Positron Emission Tomography ..... 56
Electroencephalography ..... 56
Event-Related Potentials ..... 57
Magnetoencephalography ..... 57
Transcranial Magnetic Stimulation ..... 58
Diffusion Tensor Imaging ..... 58
Theories and Models of Brain Processing ..... 59
Triune Brain Model ..... 60
Hemisphericity ..... 62
Modularity and Connectionism ..... 63
Neural Networks ..... 64
Developmental Shifts ..... 65
Theories and Models Summary ..... 68
Neuromusical Research Classifications of Related Literature ..... 69
Perception and Cognition ..... 69
Pitch Analysis ..... 72
Temporal Analysis ..... 73
Affective Responses ..... 73
Music Performance and Neuromotor Tasks ..... 75
Memory ..... 76
Plasticity ..... 77
Learning and Neural Development ..... 78
Genetic Factors ..... 78
Neurophysiological Relationships to Music ..... 79
Neural Correlates of Music Processing ..... 80
Language ..... 80
Academic Achievement ..... 81
Spatial Intelligence ..... 83
Conclusion ..... 84

III. PROCEDURES ..... 86

Restatement of the Research Purpose ..... 86
Sources of Data ..... 86
Qualifying Parameters for *MusicBIRD* Article Selection ..... 86
*MusicBIRD* Presentation Format ..... 88
Content Analysis ..... 91

IV. RESULTS ..... 92

Content Analysis ..... 93
Online Access and Word Search Protocols ..... 104

V. SUMMARY AND CONCLUSIONS ..... 111

Introduction ..... 111
Summary ..... 112
Trends in Neuromusical Research ..... 113
Methodology ..... 113
Subject Characteristics ..... 113
Musical Processes ..... 114
Implications ..... 115
Limitations ..... 120
Recommendations For Future Neuromusical Research ..... 121
Pedagogy ..... 121
Longitudinal Studies ..... 121
Further Recommendations ..... 122
Conclusion ..... 123

REFERENCES ..... 125

APPENDIX A. *MusicBIRD* REFERENCES ..... 144

LIST OF TABLES

Page

TABLE

Table 1. Descriptions of Brodmann Areas (McCaffrey, 2005) ..... 42

Table 2. Potential and qualifying articles for the *MusicBIRD* from the four electronic databases used as sources of data ..... 92

Table 3. *MusicBIRD* content analysis: *Imaging Technology*. ..... 95

Table 4. *MusicBIRD* content analysis: *Musical Processes* ..... 96

Table 5. *MusicBIRD* content analysis: *Methodology*:..... 97

Table 6. *MusicBIRD* content analysis: *Theoretical Foundations of Cognitive Neuroscience* ..... 98

Table 7. *MusicBIRD* content analysis: *Philosophical Implications*..... 98

Table 8. *MusicBIRD* content analysis: *Neurophysiology of Music Processing* ..... 99

Table 9. *MusicBIRD* content analysis: *Neuromusical Anatomy (Forebrain)*..... 101

Table 10. *MusicBIRD* content analysis: *Neuromusical Anatomy (Midbrain).* ..... 102

Table 11. *MusicBIRD* content analysis: *Neuromusical Anatomy (Hindbrain)*. ..... 103

Table 12. *MusicBIRD* content analysis: *Educational Implications* ..... 103

Table 13. *MusicBIRD* content analysis: *Neural Correlates of Music Processing*..... 103

LIST OF FIGURES

Page

Figure 1. The number of neuromusical studies found within leading research databases of health science (PubMed) and music (RILM) since 1960 ..... 20

Figure 2. Sagittal brain view (i.e., side view): Cerebral cortex lobes, cerebellum, and brain stem ..... 28

Figure 3. Sagittal brain view: cerebral cortex, limbic system, corpus callosum, brain stem, and cerebellum ..... 30

Figure 4. Common Neuron Model ..... 32

Figure 5. The Neurophysiology of Music Processing ..... 34

Figure 6. The Behavioral Level of a musical performance ..... 36

Figure 7. The Systems Level of a musical performance ..... 38

Figure 8. The Networks Level of a musical performance ..... 39

Figure 9. Sagittal brain view: Brodmann's areas across four lobes of the cerebral cortex ..... 42

Figure 10. The Cellular Level of a musical performance ..... 44

Figure 11. Average decreases in the percentage of gray matter volume from age five to twenty ..... 48

Figure 12. The Molecular (Synaptic) Level of a musical performance ..... 50

Figure 13. The Triune Brain Model ..... 61

Figure 14. Presentation format of a sample neuromusical study in the *MusicBIRD* ..... 90

Figure 15. Basic *MusicBIRD* word search procedure ..... 105

Figure 16a. Advanced *MusicBIRD* word search: Request 1 ..... 107

Figure 16b. Advanced *MusicBIRD* word search: Request 2 ..... 108

Figure 16c. Advanced *MusicBIRD* word search: Request 3..... 109

Figure 16d. Advanced *MusicBIRD* word search results..... 110

# CHAPTER I

# INTRODUCTION

People have long wondered about the mind. Before Descartes proposed "I think, therefore, I am," or even before Plato and Aristotle ever contemplated the psyche, the oldest brain map on record was being drawn upon papyrus in Egypt almost 5,000 years ago[1]. Today, neuroscientists are pursuing an age-old curiosity by drawing increasingly detailed maps of the brain with the help of imaging devices such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). Just as the telescope opened a new age of scientific discovery when Galileo first turned his lens to the night sky, the advancement of imaging technology has allowed the brain to be studied in greater detail than ever before by pushing the field of neuroscience beyond the study of the brain to the very study of what it means to be human.

The branches of brain research are reaching far and wide. In the words of John Ratey, Clinical Professor of Psychiatry at The Harvard Medical School, "For the first time ever, discoveries in the neurosciences are beginning to overlap with fields as different as anthropology, philosophy, linguistics, and psychology" (2001, p. 3). Due in part to its status as a constant human trait, one of the overlapping fields gaining the interest of the neuroscience community is music. Evidence of music has been confirmed in every civilization throughout history (Dubos, 1981; Lomax, 1968; Merriam, 1964) and

[1] The Edwin Smith Surgical papyrus describes several case studies of neurological disorders and offers the oldest recorded use of the word "brain" (Minagar, Ragheb, & Kelley, 2003)

based on research in ethnomusicology, sociology, anthropology, and neuroscience, the capacity for music processing is gaining acceptance not only as a cultural invariant, but also as a basic human trait that all people are capable of developing, especially when musical training occurs early in life. For the purposes of this dissertation, music processing is defined as any musical experience that engages the brain's cognitive, emotional or psychomotor faculties.

Consider the Venda tribe in Africa. Traditionally, every member of the tribe is expected to engage in some form of musical behavior such as singing or dancing at tribal ceremonies (Blacking, 1973). If the capacity for music processing were limited to only a select segment of the population that was born with the genetic disposition to be musical, then the culture of the Venda tribe could not exist as it does. While the Venda realized long ago that all people are capable of being musical, only recently have researchers begun to confirm that knowledge. The study of music and the brain is revealing new insights about how the brain works and with time, neuroscience may enhance understanding of how people learn to be musical as well.

## Overview of Neuroscience

Exploring the musical brain in any detail necessitates an overview of basic brain anatomy. Some might say that the human brain is a work of art in itself. With an approximate weight of three pounds, 100 billion neurons make up the cellular level of the human brain while the theorized number of synaptic pathways (i.e., connections between neurons) is around forty quadrillion ($4 \times 10^{16}$, or 40,000,000,000,000,000) (Ratey, 2001). In other words, the potential number of neural connections in each human brain is greater

than the number of elementary particles in the known universe. Needless to say, the brain is a complex system. To fully understand how the parts of the brain interact to regulate human bodily functions while simultaneously forming the essence of consciousness is something that neuroscientists are still in the process of investigating. Thus, the overview of neuroscience presented here is only a brief summary of brain regions and functions. In Chapter II, the anatomy and physiology of the brain is examined in greater detail.

Autonomic functions such as breathing, heartbeat, organ function, hormonal secretion, and emotional response are controlled by the lower regions of the brain including the brain stem, cerebellum, and the limbic system (Shepherd, 1994). In evolutionary terms, the most advanced region of the brain is the cerebral cortex, which regulates the processes for how humans become aware of their environment (i.e., perception), or how they identify and evaluate the environment (i.e., cognition). Furthermore, the cerebral cortex is believed to contain the realm of human consciousness, including personality, imagination, and aesthetic awareness.

## The Symbiosis of Music and Neuroscience

A cooperative atmosphere between musicology and neuroscience creates a mutually beneficial relationship facilitating investigations into the nature of music processing. Neuromusical research that is advantageous to musicians explores music processing based on common perspectives including: (1) a holistic approach for studying music processes, (2) the unique cognitive process of human musicality, (3) the biological role of human musicality, (4) the effect of music processing on brain development, (5)

the role of music processing in learning and memory, and (6) the philosophical implications of neuromusical research. A thorough review of peer-reviewed neuromusical literature provides an opportunity to understand how these themes of research form interacting relationships, as well as insights into the nature of music processing that are currently unforeseen. To conduct such a comprehensive review of neuromusical research has been one of the primary purposes of this dissertation.

*A Holistic Approach For Studying Musical Processes*

A widely respected approach favored by the scientific community holds that to understand the unknown, one must observe the unknown at its most fundamental level. This approach is commonly referred to as "Reductionism." Despite the tendency in neuroscience to explore the smallest details of the brain to discover the whole of its function, some neuroscientists caution against an absolute reductionist approach.

> For over half a century, modern neuroscience has been on a reductionist path, breaking things down into ever smaller parts with the hope that understanding all the little pieces will eventually explain the whole. Unfortunately, many people think that because reductionism is so often useful in solving problems, it is therefore also *sufficient* for solving them, and generations of neuroscientists have been raised on this dogma. This misapplication of reductionism leads to the perverse and tenacious belief that somehow reductionism itself will tell us how the brain works, when what is really needed are attempts to bridge different levels of discourse (Ramachandran & Blakeslee 1998, p. 264).

In essence, the need to investigate the human brain on a micro level is balanced by an equally great need to investigate the brain on a macro level in order to interpret how all the parts of the brain function together to form the whole of human consciousness. Such a qualitative, hermeneutic approach that explores how microscopic

details relate to holistic perspectives is not only necessary for establishing a valid context for basic research, it is the fundamental motivation of this dissertation. While the study of music processes may serve as a bridge to the "different levels of discourse" mentioned by Ramachandran and Blakeslee, neuromusical research is a unique opportunity for musicians to further understand the role of music in the human experience.

*The Unique Process of Human Musicality*

The idea of hemisphericity in human cognition has been presented since the 1960s as an attempt to explain how logical and mathematical functions are processed in the left cerebral hemisphere, while spatial and creative functions are processed in the right cerebral hemisphere. Although this idea has been popular (especially in the lay press), perhaps one of the most important directions that neuromusical researchers have taken is to show that music processes exist throughout the cerebral cortex. Neuromusical researchers utilize imaging devices to identify the regions of the brain that are activated during music processing, such as Electroencephalography (EEG), Event-Related Potentials (ERP), Positronic Emission Tomography (PET), Magnetic Resonance Imaging (MRI), Functional Magnetic Resonance Imaging (fMRI), Magnetoencephalography (MEG), Transcranial Magnetic Stimulation (TMS), and Diffusion Tensor Imaging (DTI). These devices are described in further detail in Chapter II.

Imaging technology has played a crucial role in the advancement of neuromusical research. Since the 1980s, researchers designing studies to examine music processing using brain imaging were among the first to show that listening to music (Mazziota, 1988) or performing music (Parsons, Sergent, Hodges, & Fox, 2005) activates regions

throughout the brain. Some neuroscientists have been openly amazed by their discovery of the unexpectedly widespread neural activity observed during music processing. For example, so encompassing were the brain regions activated by melodic listening during an early PET study that Mazziota commented, "I would be hard pressed to name areas of the brain that did not respond" (p. 108, 1988).

Due in large part to the specific detail of brain activation sites associated with music processing that have been identified with imaging technology, support is growing for a modular theory of musical processes. The theory of modularity supports the premise that the process of human musical consciousness is based on separate interacting brain areas, each of which is associated with a specific musical element such as rhythm, melody, or harmony (Altenmüller, 2001). Furthermore, it appears that the executive function of consciousness affects the degree of music processing activity as people shift their concentration from one musical aspect to another during musical experiences (Parsons, 2001). An example of shifting executive decision-making skills in music processing might be how an orchestra member focuses on pitch discrimination during tuning exercises, whereas during a concert, there may be increased neural activity in the brain areas associated with rhythm and psychomotor aspects as a complex technical passage is performed.

Before any theories are thoroughly developed about the nature of music processing, models of music processing should serve as a guide to direct neuromusical research toward a time when enough data have been collected for potential theories of music processing to be appropriately supported. Prior to the proliferation of imaging

technology, various models of brain organization were proposed, such as the evolutionary levels of the triune brain model (MacLean, 1973), or the neural network model which compares the brain to a computer's operating system (Roberts, 1989; Rolls, 1989).

Contemporary ideas about how the brain operates have strayed away from computer metaphors into more organic systems that are based on both rational and emotional processes (S. Johnson, 2005; Shepherd, 1994; Sylwester, 1995). As a result of an extended neuromusical research review and informed speculation, a detailed musical brain model has been proposed by Hodges to address ten factors that provide the structure of human music processing. These factors are:

1. All human beings are born with a musical brain,
2. The human musical brain is different from other animal brains,
3. The musical brain is in operation in infancy, and perhaps even in the later fetal stages of development,
4. The musical brain consists of an extensive neural system (or systems) involving widely distributed, but locally specialized, regions of the brain,
5. The musical brain has cognitive components,
6. The musical brain has affective components,
7. The musical brain has motor components,
8. The degree to which the musical brain is lateralized is still debated,
9. The musical brain is a very resilient system,
10. Early and ongoing musical training affects the organization of the musical brain,

With new discoveries in music processing occurring on a regular basis, it may still be too early to establish a musical brain model; however, the parameters suggested by Hodges have been especially useful for organizing the themes and topics of neuromusical research in the current study.

Three basic components of a model attempting to explain how brains engage in musical activities are motor skills, affective responses, and cognitive functions. While such a music brain model as this initially may seem like common sense to music educators, it does raise the issue of how music education attempts to address each of these model areas. One early advantage music educators may take from neuromusical research is to verify that all forms of human musicality that might occur in the human brain are being addressed by a teacher's music curriculum. Some music educators may be limiting the effectiveness of their instruction if they favor some forms of music processing more than others, especially the music processes that are shared with nonmusical brain systems such as language, visual, or psychomotor processes. Further neuromusical research is warranted to investigate the music-language interaction of singing words, and the psychomotor and visual relationships involved with activities such as marching, dancing, conducting, or *Eurhythmics,* an instructional method made popular by Emile Jaques-Dalcroze (1865-1950) to increase musical sensitivity through physical exercise (Mark, 1996).

*The Biological Value of Human Musicality*

Evolutionary theories of why humans are musical pose an interesting quandary in that such theories can only be hypothesized, and, short of inventing a time machine to

track the development of human music practices, these theories can never be soundly proven or denounced either. However, this dilemma has not stopped people from wondering why humans are musical. Debate continues over whether music serves an evolutionary adaptive role that enhances human life by serving some survival need, or, in the words of Steven Pinker, whether music is just some kind of "auditory cheesecake" that provides a pleasurable effect due to the way the auditory cortex and the rest of the brain process sounds though not necessarily to provide any greater purpose for basic human needs (Pinker 1997, p. 534).

For those who suggest that music has evolved to serve the needs of humankind, some theories include: (1) music developed out of the mating interests and rituals of prehistoric humans (Darwin, 1871; G. F. Miller, 2000), (2) musical sounds serve socialization needs such as eliciting a bond between a mother and her baby (Hodges, 1996a), (3) music serves to form cooperative relationships within social groups (Hagen & Bryant, 2003), (4) the evolutionary origins of music may be related to language with music serving as a precursor to language by helping early humans to identify and organize sounds (Roederer, 1982), or (5) that both language and music consist of a knowledge base of sounds that are instantly recognizable to language (Chomsky, 1986) or music (Hauser & McDermott, 2003). An in-depth investigation of some of the evolutionary theories supporting the development of music processing are presented in *The Origins of Music* (Wallin, Merker, & Brown, 2000).

From a more anthropological perspective, Alan Merriam and E. Thayer Gaston proposed several reasons supporting the aesthetic values and biological purposes for

human musicality. As an anthropologist, Merriam observed many cultures around the world to identify ten functions of music in society including: (1) emotional expression, (2) aesthetic enjoyment, (3) entertainment, (4) communication, (5) symbolic representation, (6) physical response, (7) enforcing conformity to social norms, (8) validating social institutions and religious rituals, (9) providing continuity and stability of culture, and (10) facilitating social integration (Merriam, 1964).

Based on a similar perspective, Gaston's eight considerations of how music affects human behaviors and needs are: (1) all humans need aesthetic expression and experiences, (2) musical experiences are culturally determined, (3) music has spiritual significance, (4) music is communication, (5) music structures reality, (6) music is derived from the deepest and most tender human emotions, (7) music serves as a source of personal gratification, and (8) the potency of musical affects are greatest in social interactions (Gaston, 1968). Among all of these considerations, Gaston valued music the most for the unique way it allows people to pursue meaningful aesthetic experiences.

Although some people (such as those from the formalist ideology) may be uncomfortable citing the nonmusical values of music to humankind, the paradox of these considerations and functions is that one can never truly know whether music has evolved to fulfill nonmusical purposes in ways that only music can, or whether music has developed for intrinsically musical reasons based on pleasurable auditory stimulation. Furthermore, perhaps music evolved as a combination of both these possibilities. While neuromusical research seeks to understand *how* humans are musical, it is unlikely that an absolute answer will be found to fully explain *why* humans are musical.

*Musical Morphology: The Effect of Music Processing on Brain Growth*

Plasticity refers to the way that developing neural pathways are affected by external factors in the environment. Individuals with musical training are more likely to affect the size and neural complexity of brain regions associated with music compared to other individuals without musical training. Brain morphology is affected by all experiences, not just the musical ones. Results of research on musical morphology, however, are strong not only for the information yielded about how the brain develops, but also for the implications of how changes in the brain due to music processing may correlate to non-music processes as well. These correlates will be explored in more detail in the following section, *The Role of Music Processing in Learning and Memory*, and in even further detail in Chapter II. The current section in Chapter I is limited to observed changes in the size of brain regions due to music processing.

Multiple neuromusical researchers have observed that several regions in the brains of musically trained individuals are significantly larger than the same areas in the brains of nonmusically trained individuals. These affected areas include: (1) the corpus callosum (a bundle of neural fibers connecting the left and right hemispheres of the brain) (Schlaug, Jäncke, Huang, & Steinmetz, 1995), (2) the motor cortex (the brain region responsible for controlling muscle activity) (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Pantev, Engelien, Candia, & Elbert, 2001), (3) the cerebellum (brain region responsible for coordinating fine motor skills with sensory information) (Hutchinson, Lee, Gaab, & Schlaug, 2003), (4) the planum temporale (PT) (a sound processing

structure within the auditory cortex) (Schlaug, Jäncke, Huang, & Steinmetz, 1994), and (5) overall increased gray matter (Gaser & Schlaug, 2003; Sluming et al., 2002).

Differences in the size of the left hemisphere planum temporale is even greater for children who began their musical training before age seven (Schlaug, Jäncke, Huang, & Steinmetz, 1995). Musical training of children appears to enhance auditory synaptic development in the brain; thus, fueling speculation that musical training may strengthen existing neural pathways in young brains and possibly even add new neural pathways. Furthermore, this developmental effect appears to be age dependent. There is extensive evidence showing that without musical training at an early age, the development of Absolute Pitch (AP) is extremely rare (Baharloo, Service, & Risch, 2000; Miyazaki, 1988; Zatorre, 2003). Absolute Pitch is the ability to identify a pitch without first hearing a reference pitch. For musicians with AP, the left PT is more than twice the size of individuals without musical training (Schlaug, Jäncke, Huang, & Steinmetz, 1995).

*The Role of Music Processing in Learning and Memory*

For those who wonder what neuromusical research could possibly have to offer music education, the basic question that should be asked is, "What profession would *not* stand to benefit from the advancements of neuroscience?" People from disciplines as diverse as philosophy, education, and medicine have benefited from neuroscience research by applying insights about how the brain works in relation to solutions for problems in their own field. Some of these applications may help save lives by allowing physicians to target and possibly treat the early signs of Alzheimer's disease through brain imaging research. Other applications of though, may challenge ethical principles. For example,

some corporations have begun using brain imaging techniques to recognize the personality traits that would help to identify the people best suited for certain jobs (Pepper, 2005). As with any new technology, the ethical responsibility of how neuroscience is applied to other disciplines should be conducted in an open discussion of the positive or negative consequences of neuroscience spin-offs.

When considering the effect of music processing on brain development, many researchers are interested in whether musical processing has any effect on nonmusical brain functions. Although this is an intriguing question (especially to educators), a review of current neuromusical research is still not extensive enough to draw any strong conclusions on the neural correlates of music processing that students could apply to academic achievement (Hodges & O'Connell, 2005). To conclusively make inferences about the relationship of music processing, brain morphology, and cognitive development requires many longitudinal studies to track the progress of children throughout the course of their music education. Such long-term goals are being currently pursued by Pantev and his colleagues in an extensive brain imaging study to investigate the morphology and cognitive development of children using the Suzuki violin method from age four to adulthood (Abbott, 2002).

In learning situations, studies with EEG have shown that during the initial experience of a new activity (e.g., playing the piano for the first time), neural pathways are established during the first few minutes that will determine how the brain will engage its learned memories of this activity again in the future (Bangert & Altenmüller, 2003). In other words, the way people learn to play an instrument during their first lesson may

set the neural foundation for the way their brain engages the process of playing that instrument for the rest of their lives. This finding supports teachers who already stress the need for clarity during an initial learning experience, and refutes ideas that learning a new skill can be altered easily at any stage of a person's development.

Regarding memory, research in psychology has shown that students who receive musical training have a better recall of language memory than nonmusically trained students (Ho, Cheung, & Chan, 2003). Such studies lead to questions of whether musical tasks share the same areas of the brain as other nonmusical tasks (e.g., language). In terms of which areas of the brain are activated relative to various tasks, it appears that musical brain functions may: (1) share the same neural area as other nonmusical brain functions, (2) use different sub-areas of similar regions, or (3) are disassociated and unique from all other brain function areas.

Based on these widespread possibilities of musical brain activation sites, there is some research suggesting that language and music processes may share similar or at least related areas of the brain. Although studies that suggest the nonmusical benefits of musical experiences are interesting and even exciting to advocates of music education, a note of caution should be sounded among those who enthusiastically embrace early research results suggesting possible neural correlates of musical processes (i.e., nonmusical mental abilities that are enhanced by musical experiences). While further investigations along this vein should be conducted carefully, the absolute claim that music instruction improves performance in other subjects should patiently wait until additional research is in place to support such ideas.

To claim conclusively that musical training improves the mental processes of other disciplines is a dangerous position for music educators to endorse. First of all, the identification of generalizable relationships or correlates does not necessarily support cause and effect relationships. Furthermore, if future neuromusical research definitively shows that musical experiences do not share a relationship with improved student performance in other subjects any more than other mentally stimulating activities (e.g., chess or team sports), then the music education profession could seriously lose credibility and value in the curriculum of modern schooling. On the other hand, if neural correlates of music processing do exist then neuromusical research may be one of the best ways to identify these relationships.

*The Philosophical Implications of Neuromusical Research*

As neuroscientists delve deeper into the study of the brain, it is fascinating to witness the discovery of new philosophical issues as well. Neuroscience is lending support to a branch of philosophers known as physicalists, who support the idea that the nature of the self, the soul, and consciousness is found strictly within the nervous system. As a physicalist, Churchland (2003) has written extensively in opposition to functionalism, the prevailing philosophy of modern academia that holds that the sense of self exists beyond the physical realm of the nervous system. Physicalists have found evidence for self-representational capacities existing solely in the nervous system based on evidence from studies exploring the effect of neurological damage (e.g., schizophrenia) on the sense of self (Stephens & Graham, 2000) and even experiments with induced sensations of spiritual transcendence via temporal lobe stimulation (Booth,

Koren, & Persinger, 2005). Though challenging to the traditional functionalist philosophy, the physicalist perspective claims to enhance the knowledge of self for the purposes of social good and moral clarity (Moss, 2003).

From a more musical perspective, Halpern has conducted several brain imaging studies to identify the various regions of the brain that are engaged with music processing (Halpern & Zatorre, 1999; Halpern, Zatorre, Bouffard, & Johnson, 2004). When asked during a roundtable discussion how her research applies to education, she stated her belief that humans are born with implicit knowledge allowing them to recognize and respond to the explicit knowledge gained during learning experiences (Hodges, 2000b). In terms of music education, her statement implies that humans are inherently equipped with the means to recognize and respond to the musical experiences that are presented to them.

On a philosophical level, this idea relates to Bennett Reimer's aesthetic theory of absolute expressionism which basically says the same thing: music is meaningful because in its intrinsic qualities, it presents the patterns and forms (i.e., explicit knowledge) of human responsiveness (i.e., implicit knowledge). Reimer writes:

> Because experiences of art yield insights into human subjectivity, the arts may be conceived as a means of self-understanding, a way by which our sense of our human nature can be explored and clarified and grasped (1989, p. 53).

Support for Halpern's idea and Reimer's theory is coming from some of the most unexpected places. Neurobiologists studying the relatively simple neural circuit of marine snails (*Aplysia*) discovered what might be the first evidence for the fundamental

structure of implicit knowledge (Kandel & Mack, 2003). When observing how various snails responded to a gill stimulus, researchers were surprised to find that not only was the gill's reflex behavior invariant among snails, but a form of pre-knowledge was suggested as the nerve cells engaged in the reflex process were interconnected in exactly the same neural pattern for every animal that was examined. "We saw that built into the brain, under genetic and developmental control, is the very basic architecture of behavior" (p. 278).

Implicit knowledge is implied by the consistency of the original neural pattern for each snail. On the other hand, explicit knowledge affects the strength of each neural pathway based on the learning experiences from each snail's environment. Moving from a reductionist-snail-neuroanatomy-viewpoint to the wider perspective of human musical responsiveness is not as difficult as one might think. Just as each snail has the same original neural circuitry affecting how it responds to its environment, each person may also be equipped with a much more complex, yet very consistently human neural foundation. At one point in the search for why humans have evolved to have greater cognitive abilities than other animals, neuroscientists had thought they might find that human neurons were unique. Quite to the contrary however, human neurons are just like those of any other animal (Stillings et al., 1995).

Thus, the understanding of cognitive comparisons between human and animal, or even one human to another is not only based on *what* brains are made of; it is primarily based on *how* brains are neurally organized. In terms of music processing, the invariance of art and music throughout the history of human civilization is powerful evidence that,

while every person's brain is a unique combination of genetic and environmental factors, every human is also fundamentally alike in the way that each brain is similarly structured to react to the context of life. People all over the world respond to scenes of nature or the sounds of music in different ways, but the important thing to recognize is that *everyone* responds. As neuroscientists continue to investigate the brain, there will be a great need for all involved to wisely address how this growing field is approaching a fine line between science and philosophy.

As for how neuromusical research directly applies to music education, it is still too early to develop any solid theories of how neuromusical experiences relate to music learning. There is an increasing interest among music educators to look to the field of neuromusical research for insights into music learning and pedagogy as evidenced by the forthcoming book, "Neurosciences in Music Pedagogy" (Gruhn & Rauscher, 2007). As noted in Chapter I, a growing band of music educators are seeking connections between neuroscience and music education, such as Steven Demorest (Demorest, 2000), John Flohr (Flohr & Hodges, 2002), Donna Fox (D. Fox, 2000) and Donald Hodges (Hodges, 2000a). Ultimately, efforts in neuromusical research may serve to enhance the understanding of how humans learn to be musical, as well as to inspire a sorely needed growth of philosophical research in music education by exploring the nature of human musicality.

## Development of the Dissertation Idea

An argument has been made thus far to show the symbiotic relationship that exists between research in music and neuroscience. Based on its ubiquity throughout humanity

combined with the widely distributed areas of music processing that have been observed in the brain, music offers neuroscientists a unique perspective for research. On the other hand, neuroscience offers an equally unique perspective for exploring the pedagogical, psychological, and philosophical foundations of music education.

Furthermore, interest in neuromusical correlates (i.e., nonmusical processes that share a relationship with musical processes) is giving rise to an increasingly large number of neuromusical studies published in peer-reviewed journals. To explain this growing enthusiasm for neuromusical research, consider the comments of two prominent neuromusical researchers, Isabelle Peretz and Robert Zatorre, co-editors of the book, *The Cognitive Neuroscience of Music*:

> This sudden increase in scientific work on music has been motivated in part by the idea that music offers a unique opportunity to better understand the organization of the human brain. The other major motivation for exploring the neural substrates of musical activities is that they may shed light on the functional origin and biological value of music (2003, p. v).

Many researchers share this perspective and have been motivated to study the neural substrates of music (i.e., the myriad ways that the human central nervous system engages in musical experiences). Figure 1 graphically depicts the rapid growth in neuromusical research through the last 45 years, especially since the advent of brain imaging technology in the 1980s. In addition, the past decade has seen the rise of several international conferences for the purpose of sharing current neuromusical research (e.g., *The Biological Foundations of Mu*sic, 2000; *The Neurosciences and Music*, 2003; *The*

*Neurosciences and Music II*, 2005; and eight occurrences of *The International Conference on Music Perception and Cognition* which meets biannually). Based on this growing interest, it is clear that neuromusical research is a growing field of study that would benefit from a comprehensive review of its research.

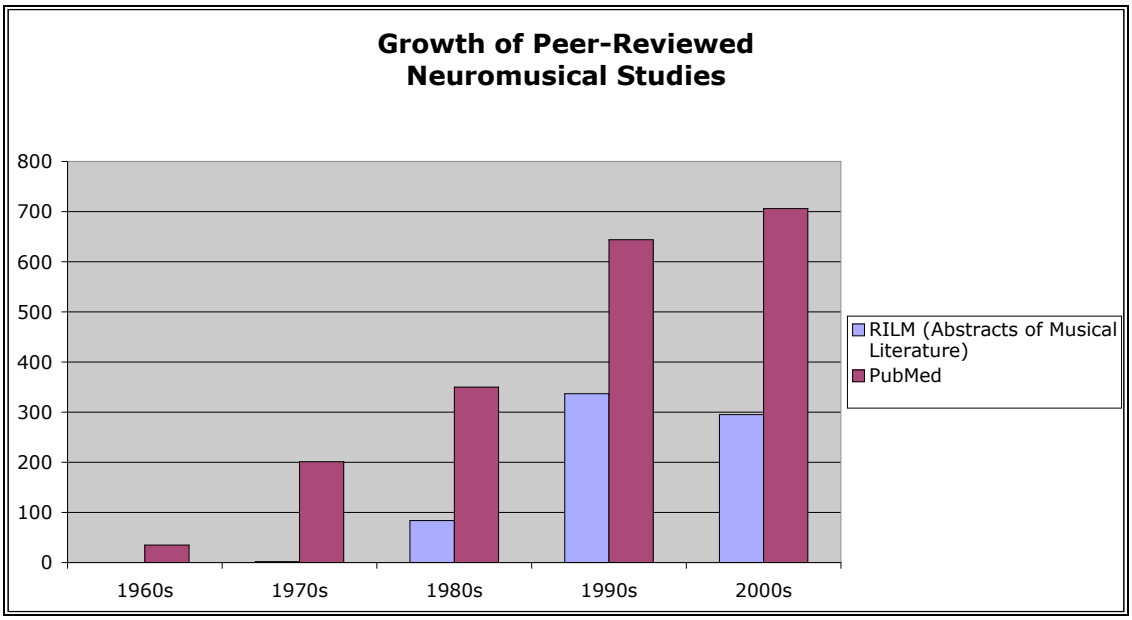



Figure 1. The number of neuromusical studies found within leading research databases of health science (PubMed) and music (RILM) since 1960. Studies were identified within RILM by a keyword search for "brain" whereas PubMed used the keywords "music" and "brain".

*Research Problem*

Given the advent of brain imaging technology connected to the rising number of neuromusical studies, in conjunction with a lack of comprehensive research to interpretatively connect these studies, there is a clear need to compile neuromusical research into a summative database. Prior to this dissertation, no such resource has existed. Without an all-inclusive means to account for developments in neuromusical

research, a generalizable understanding of the brain's musical functions will be limited, if at all feasible. Thus, the application of neuromusical research to other disciplines will lack credibility until a holistic perspective of the extant neuromusical research is made available.

*Research Purpose*

The primary objective of this dissertation was to assess and clarify the current state of neuromusical research by creating an online database to present summative information from all peer-reviewed studies of brain imaging neuromusical research. Titled the Musical Brain Imaging Research Database (*MusicBIRD*), it contains studies selected from the following resources.

1. Peer-reviewed journals containing neuromusical research presented in the electronic databases PubMed, PsychINFO, ERIC, and RILM.

2. Additional sources (e.g., edited book sections, conference proceedings, or poster presentations) selected at the researcher's discretion based on a source's relevancy to the field of neuromusical research.

The secondary research objectives were as follows:

1. To identify any trends across the field of neuromusical research regarding the frequency of research tasks, methodology, and research topics,

2. To reveal any implications from neuromusical research serving the pedagogical, psychological and philosophical foundations of music education, and

3. To identify future areas of neuromusical research.

*Scope of the Study*

The scope of this study was widespread and the possibility for omitting some research from the final database was a risk; however, with comprehensive online databases of peer-reviewed research such as PubMed and RILM, there is great confidence that a vast majority of neuromusical studies are available for compilation and evaluation. The challenge of compiling these studies into a database was and continues to be a necessary step for setting the foundation of neuromusical research.

To focus the attention of musicians on the field of neuroscience is not only feasible, it is ultimately desirable. Up to the point of this dissertation, most neuromusical researchers sought to understand the brain by exploring musical processes from the perspective of the neuroscientist. Yet, building a bridge to "different levels of discourse" requires input from diverse areas of expertise. An extremely focused approach, such as reductionism, may yield important discoveries, but perspectives that are limited to only the specific details are the basis of cautionary axioms like "You can't see the forest for the trees." A neuroscientist's perspective of music processing could be well balanced by the insight of a musician. In other words, the time has come for music researchers to engage neuroscience and build a holistic praxis of interdisciplinary cooperation.

# CHAPTER II

# A MUSICIAN'S GUIDE TO NEUROSCIENCE AND RELATED LITERATURE

The reason that neuroscience appeals to so many different disciplines is that the brain is fundamentally responsible for every human activity. From music and athletics to philosophy and quantum theory, each endeavor is based on the brain's ability to function. Thus, the study of the brain is not only opening a window into sciences like medicine and psychology; it is exploring the very foundation of what it means to be human, and neuromusical research offers a unique perspective in that search.

The purpose of this chapter is to systematically address the necessary information needed to understand the scope of neuromusical research from a musician's perspective. Learning how the brain and the Central Nervous System work can be a confusing task given that there are several different approaches to describe how the parts of the brain are labeled. For example, a neuropsychologist might refer to Broca's areas whereas a neurobiologist referring to Brodman areas 44, 45, and 46 would be referring to the same place in the brain (Stafford & Webb 2005, p. 15). Furthermore, the "cerebral cortex" is also known as the "cerebrum" or the "neocortex" depending on the source.

Despite these complexities, the following topics provide the foundation to the design and utilization of a neuromusical research database:

- Brain anatomy
- Neurophysiology

- Descriptions of brain imaging technology
- Theories and models of brain processes
- Neuromusical research classifications and related literature

To explain what is known about the brain's role in the process of human musicality, the context of this chapter is a limited space to present such widespread information. However, the research purpose of this research project mandates that both the author *and* the reader share an adequate understanding of how the brain functions. Thus, the information in this chapter is intended as an introduction to neuroscience and will hopefully lead the reader to more authoritative resources. For further reading about the brain, cognitive psychology and neuroscience, the following books range from a layman's perspective (Carter & Frith, 1998; Drubach, 2000; Ratey, 2001; Sylwester, 1995) to more professional laden terminology (Kandel, Schwartz & Jessell, 2000; Shepherd, 1994; Stillings et al., 1995) to comprehensive reviews of music psychology (Deutsch, 1999; Hodges, 1996c).

## Neuroanatomy

The Central Nervous System (CNS) includes the brain, the brain stem, and the spinal cord. Nerve cells, or neurons, have two types: receptor nerves are responsible for receiving sensory information from environmental stimuli and then sending this information to the brain via the spinal cord along afferent nerve pathways; effector nerves send messages from the brain out to the

muscles along efferent nerve pathways to tell each muscle how and when to move (Shepherd, 1994).

Much of the discussion in this chapter focuses on identifying and describing the parts and regions of the brain and the human processes associated with the control of these processes from the smallest muscle movement to the most complex abstract thought. At approximately three pounds, the brain contributes only around 2% of a human's average weight, however, it uses almost 20% of the blood and oxygen in the circulatory system (Stafford & Webb, 2005). In fact, measuring the flow of blood in the brain with PET or MRI scans is one of the most common methods of quantifying brain activity.

The whole brain consists of three basic divisions: the forebrain, the midbrain, and the hindbrain. The hindbrain includes the cerebellum, pons, and medulla oblongata and it is primarily concerned with autonomic (i.e., involuntary) processes such as the regulation of breathing and heartbeat (Sylwester, 1995). The midbrain has a reduced role in mammals and primarily serves as a connective area between the motor neurons and the higher-order processes of the forebrain. In fact, the midbrain does not contain any distinctive regions or modules and thus, it will not be reviewed any further in this chapter. Positioned atop of the other divisions, the forebrain is the largest part of the brain and is associated with behavior, short and long-term memory, learning, motor skills, vision, hearing, affective responses, creativity, and decision-making.

*Hindbrain: The Brain Stem and Cerebellum*

The hindbrain consists of the brainstem (pons and medulla oblongata) which forms a link between the cerebral cortex, white matter, and the spinal cord (Drubach, 2000). The brain stem is characterized by a central core of gray matter (i.e., unmyelinated nerve fibers) known as the reticular formation, which serves as a filter for incoming information to the cerebral cortex. Considered to be the oldest evolutionarily part of the brain, the hindbrain is chiefly responsible for regulating the autonomic functions in the body.

*Forebrain: The Cerebral Cortex*

The forebrain consists mainly of the cerebrum, which resides at the top portion of the brain. The cerebrum, or cerebral cortex, is equally divided into two hemispheres that communicate via the corpus callosum, a thick connective bridge of neurons that allow each hemisphere to work with the other while still maintaining separate hemispheric traits and systems. Except for the small pineal gland located at the center of the brain, every part of the brain is duplicated in each hemisphere (Carter & Frith, 1998). As for the overall traits of each hemisphere, the left hemisphere (LH) is more involved in sequential processing while the right hemisphere (RH) is more involved in holistic processing. In musical terms, while music processing has been found to activate regions throughout the brain, it is more prevalent in the RH, especially when creative musical aspects are actively involved (Li et al., 2000; Tervaniemi et al., 2000; Vollmer-Haase, Finke, Hartje, & Bulla-Hellwig, 1998).

The cerebral cortex is approximately two to four millimeters thick, and if unfolded and unwrinkled, it would reveal itself to be roughly the size of an open newspaper, or about 1.5 square meters (Stafford & Webb, 2005). This thin layer of gray matter has evolved to fold in on itself in order to fit a large amount of neural tissue into a relatively small space (i.e., the cranium). The wrinkles in the cerebral cortex are occur due to the folding process, in which each gyrus (plural: gyri) is a wrinkle or fold on the cerebral cortex representing a region where neurons have linked together into a compact lattice of neural circuits. The opposite of a gyral bulge is a sulcus (plural: sulci), which is a groove or furrow in the cerebral cortex where neurons have not grown together. These wrinkles and grooves also serve as lines of demarcation to separate the four lobes of the cerebral cortex as shown in Figure 2.

While general cognitive aspects of the systems located within each lobe can be inferred based on brain imaging research and neurological studies of brain damaged patients, much is yet to be learned about how the networks and systems of the brain work together to create conscious behaviors. As shown in Figure 2, the occipital lobe primarily deals with visual systems; the parietal lobe controls the neural systems related to movement, orientation, and calculation; the temporal lobe contains the auditory cortex which processes all things related to sound (e.g., speech or music) as well as dealing with some aspects of memory; and the frontal lobe addresses central cognitive functions such as thinking, planning, evaluating, and making decisions (Drubach, 2000).

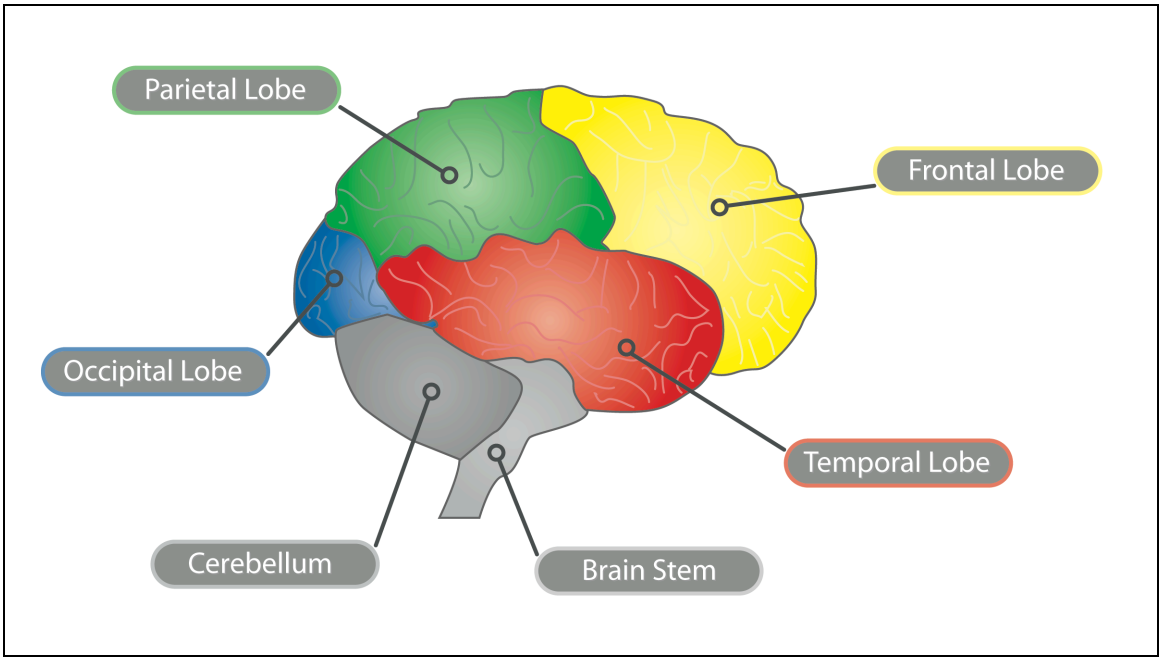



Figure 2. Sagittal brain view (i.e., side view): Cerebral cortex lobes, cerebellum, and brain stem (figure adapted from an illustration in Carter & Frith, 1998).

Within each lobe are three basic zones responsible for processing information coming from a person's environment, as well as for generating functions that allow a person to adapt to the environment. These guiding zones within each lobe that holistically organize the cerebral process are (1) sensory, (2) motor, and (3) associative (Shepherd, 1994). Environmental stimuli (e.g., sight, sound, touch, taste, and smell) are sent to the brain via afferent nerves to be processed by sensory zones in the brain. The body's muscular controls are processed by motor zones that send bodily movement directions from the brain along efferent nerve pathways to muscle groups. Associative zones deal with the higher-level cognitive functions of human thought by comparing and contrasting the whole of neural information from memory, sensory, motor, and affective functions. Shepherd writes that it is the associative zones' capacity for multimodal

integration of information across cerebral lobes that separates humans from other animals: "The capacity to integrate higher-order sensory information and use it to control different kinds of motor outputs lies at the heart of many of our higher cognitive functions" (1994, 671).

*The Limbic System*

Lying directly beneath the cerebrum is the limbic system (Figure 3), an assortment of adjacent modules and regions from the frontal, parietal, and temporal lobes surrounding the corpus callosum. Each of the limbic system's parts occur in varying sizes that are responsible for regulating emotions and urges as well as several other important functions such as long-term memory (Carter & Frith, 1998). The modules of the limbic system include the hypothalamus and the pituitary gland (serving to regulate the body's daily needs such as metabolism and sleep cycle), the thalamus (a relay station for the processing of incoming sensory information), the amygdala (regulating the fear response) and the hippocampus (long-term memory regulation and fear oriented emotions). The limbic system plays such a crucial role in the human condition that some neuroscientists enjoy proclaiming that it regulates the four F's of human survival: Feeding, Fighting, Fleeing, and Mating (Stafford & Webb, 2005).

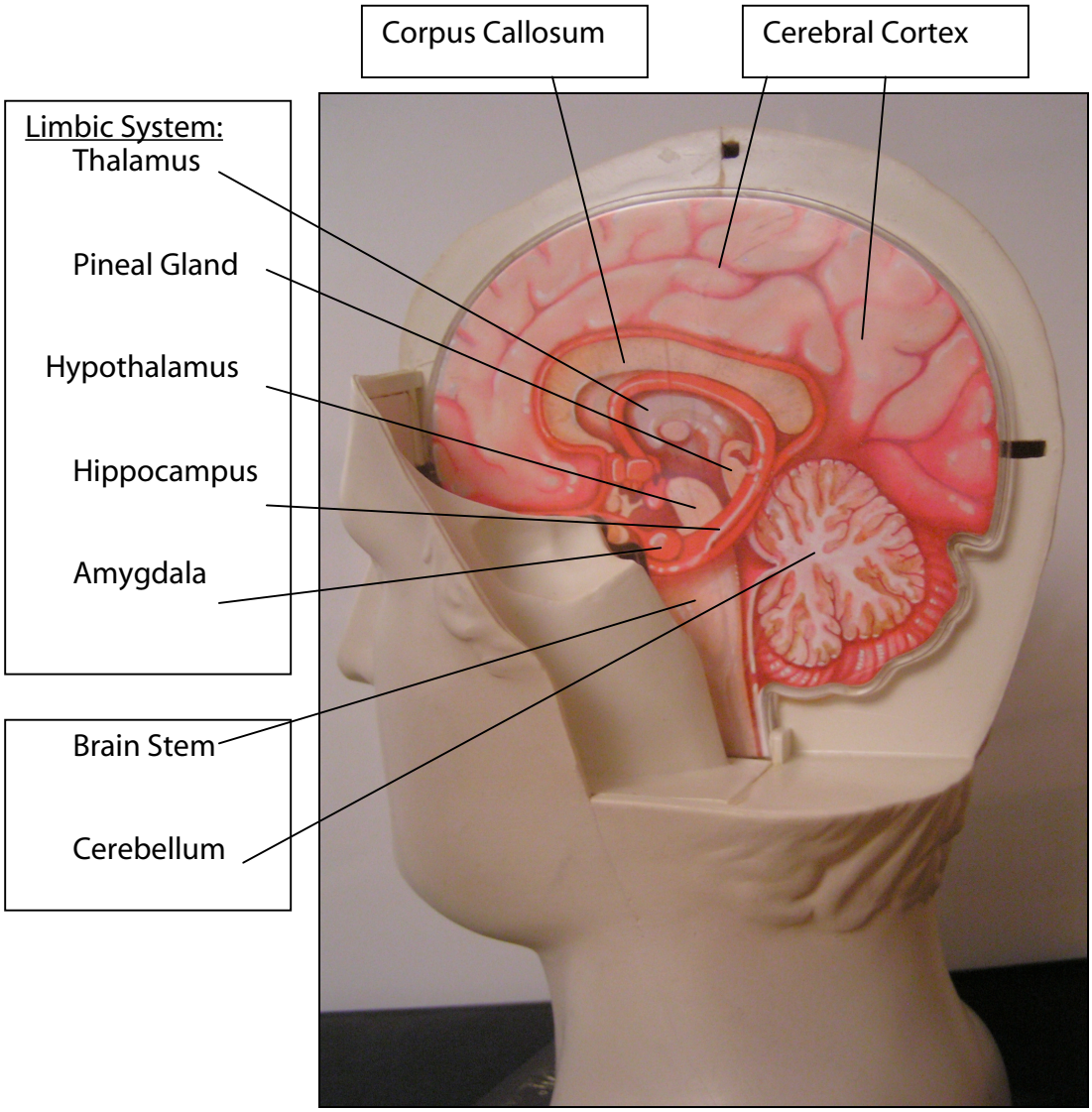



Figure 3. Sagittal brain view: cerebral cortex, limbic system, corpus callosum, brain stem, and cerebellum (photograph provided by the author).

*Brain Cells*

Before moving on to an explanation of the brain's physiology, it will be helpful to have a better understanding of the main types of brain cells: glial cells and neurons. In addition to the 100 billion neurons in the brain, there are as many as 50 trillion glial cells

which serve as the supporting structure of the central nervous system by surrounding cell bodies, axons, and dendrites (Kandel et al., 2000). Glial cells are especially crucial for the development of myelin (i.e., white matter) along the axon sheath that is formed as neural pathways are used more frequently.

Neurons are specialized nerve cells that send electro-chemical impulses between one another to serve as the circuitry of the CNS. The typical neuron (Figure 4) consists of three main parts: (1) the soma (the cell body containing the nucleus, mitochondria, and vesicles); (2) the axon, (which sends a neuron's chemical information in the form of neurotransmitters to other nearby neurons); and (3) the dendrites (a series of receptive branches to collect the neurotransmitters sent by the axons of other neurons). Neurotransmitters and the process of neural communication are explained in more detail in the following section on neurophysiology.

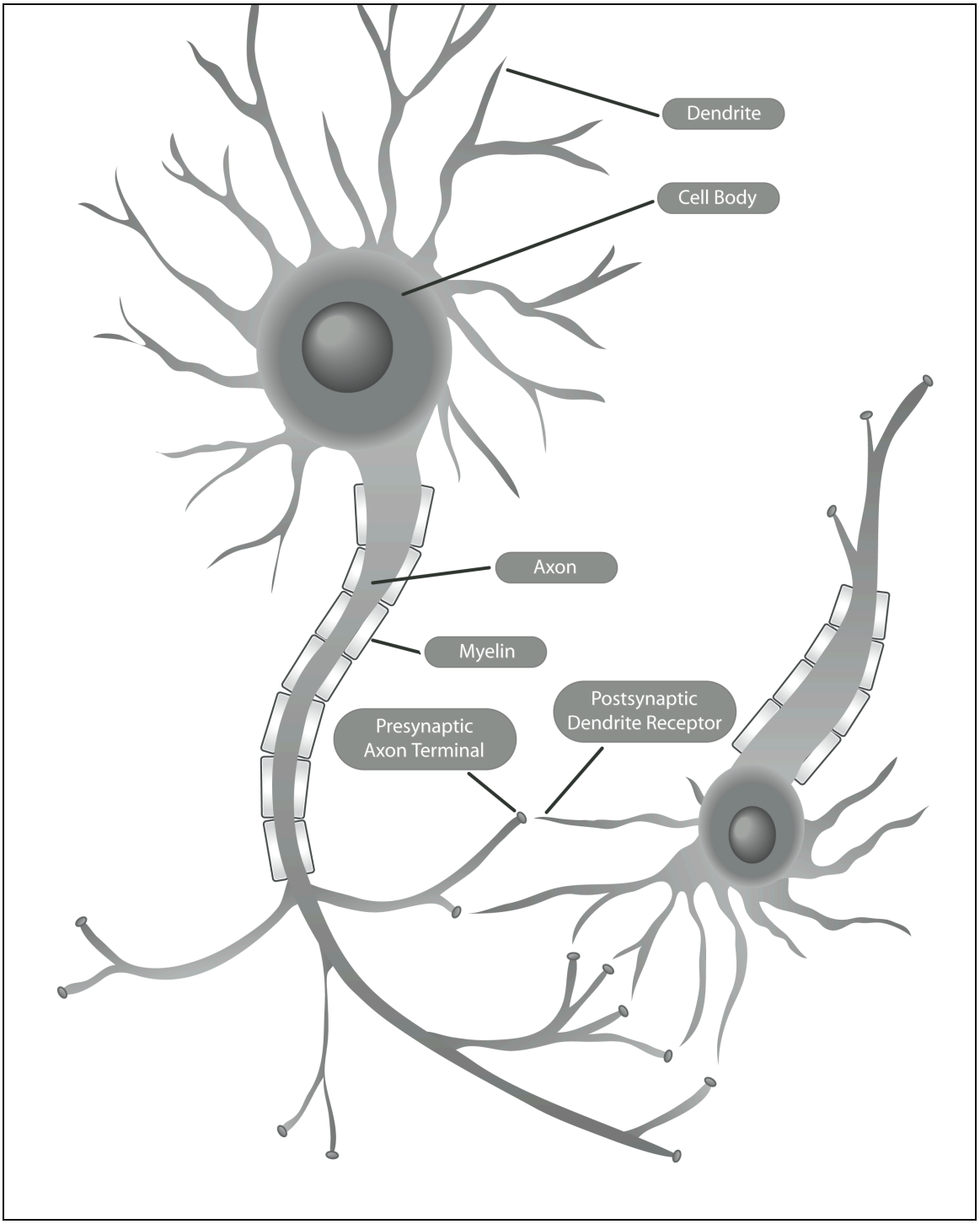



Figure 4. Common Neuron Model (figure adapted from a sketch by the author)

## Neurophysiology

While neuroanatomists study the structure of the brain, neurophysiologists study how the brain operates. Neurophysiology is the branch of biology dedicated to the study of brain and its parts and how each of these parts are involved in the different levels of brain activity. In other words, each element of brain activity, be it explicit behaviors or even the path of a single neurotransmitter, is interconnected and thereby affecting the overall operation of the brain, which in turn is involved in each human behavior. Considering the roughly 100 billion neurons that are involved in this process, neurophysiology is a daunting pursuit, but progress is coming one brain scan at a time. Presented in order from largest to smallest magnitude, the processes within the human brain can be organized along the following levels:

Behavioral
↕
*Systems*
↕
*Networks*
↕
*Cellular (Neural)*
↕
*Molecular (Synaptic)*
↕
*Genetic*

For example, Figure 5 presents a conceptual illustration from the Behavioral to the Molecular neurophysiological levels involved in a musical performance.

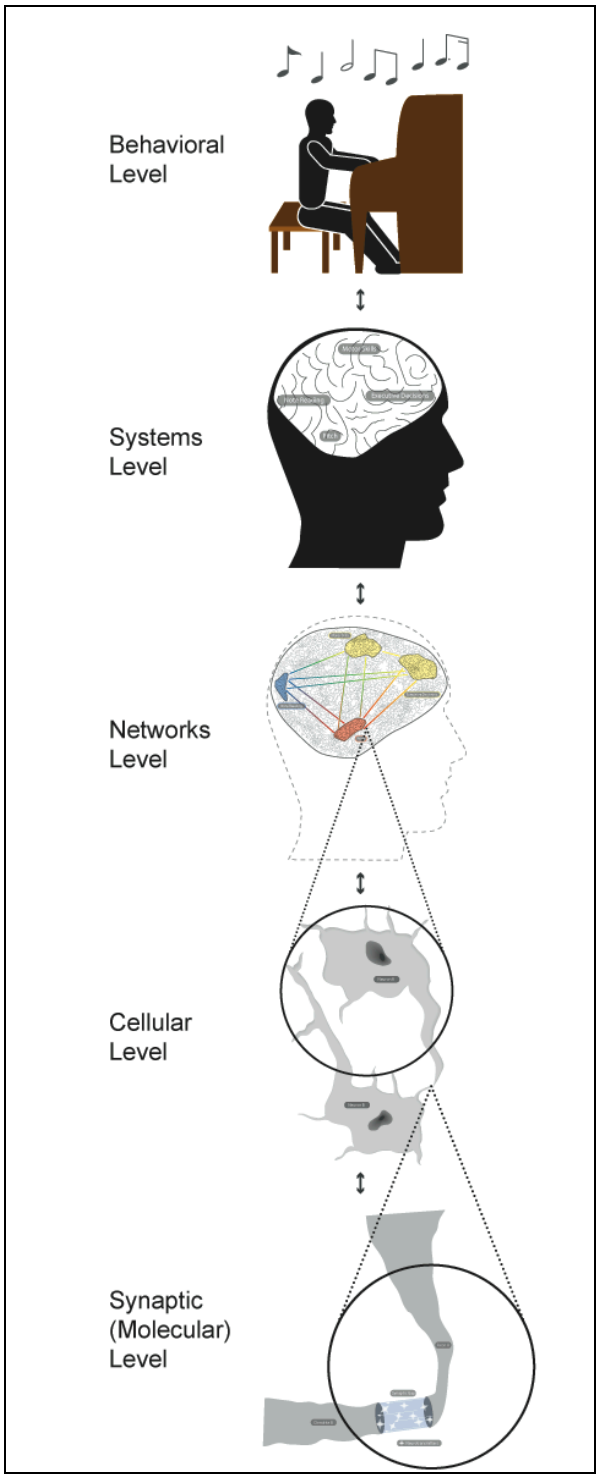



Figure 5. The Neurophysiology of Music Processing. This illustration presents a conceptual perspective of piano performance from the behavioral level to the molecular level (figure adapted from a sketch by the author).

Currently, the molecular and synaptic levels are the most researched areas of neuroscience which is not surprising given the role of the reductionist approach addressed in Chapter I, yet great efforts are being made to draw connections between how the microscopic levels of neurophysiology relate to macroscopic levels like systems and behaviors (Stillings et al., 1995). For example, the development of any theories of music processing related to how music performance skills are acquired would be based on a thorough understanding of the systems level, possibly with regard to how the motor and auditory cortices work together with the emotional regulation of the limbic system and the decision making ability of the executive function. On the other hand, if one were interested in how musical timbre becomes a part of the brain's tonal memory, such knowledge would range somewhere between the synaptic and network level.

*The Behavioral Level*

Ultimately, human behavior is the culmination of multiple interacting neural systems in the brain and each system is based on millions of similarly specialized neural networks firing together. Thus, any investigation of the learned behaviors associated with musical performance (such as the piano performance depicted in Figure 6) would not only address how musical aspects like melody, harmony, and rhythm are processed in the brain, but also how fine motor skills (i.e., muscle movements controlling small, precise actions) and visual note reading behaviors occur as well.

Cognitive psychologists and neuroscientists seeking to understand human behavior through the study of neurophysiology still have a long way to go before any meaningful connections can be drawn between the molecular and behavioral levels.

Before neuromusical researchers can approach a more holistic study of musical concepts (e.g., form, or thematic development), they have initially been focusing on the minutiae of musical concepts (e.g., pitch and rhythmic perception). As the study of neuroscience continues to advance up the reductionist ladder to the point where the sub-levels below behavior are more fully understood, there may be a time in the future when psychology and neuroscience combine to explain the neurophysiology of human behavior.

Figure 6. The Behavioral Level of a musical performance. In this figure, playing the piano represents a learned behavior based on the interaction of multiple systems in the brain (figure adapted from a sketch by the author).

*The Systems Level*

The major systems of the brain that provide the highest level of cognitive organization are distributed across the cerebral cortex. These major systems are categorized as somatosensory (e.g., hearing, touch, taste, smell, and sight), neuromotor (i.e., large and fine muscle control), affective (e.g., emotional responses) and central (i.e., executive functions involving ideas, evaluations, and decisions) (Shepherd 1994, 7). Autonomic systems that regulate organs, emotions, and bodily functions are located in the brain stem and cerebellum (i.e., the hindbrain). A general model of the music-related systems associated with piano performance is presented in Figure 7.

A classic example of a neurophysiological system is in the area of the cerebral cortex known as "Wernicke's area." This area of the brain controls the system that interprets meaning from sounds, primarily words. Conversely, "Broca's area" in the brain controls the ability to generate meaningful speech. Each system is reliant upon specific areas of the brain such as the auditory cortex (hearing), the visual cortex (vision), or the somatosensory cortex (sensory-motor skills). Theories conflict, however, on whether music processes exist in a unique area of the brain as a system that is separate unto itself (i.e., modular brain theory) or whether music exists as the gestalt of all systems directed toward a musical task (i.e., connectionism). This debate is examined further in the section *Theories and Models of Brain Processing*.

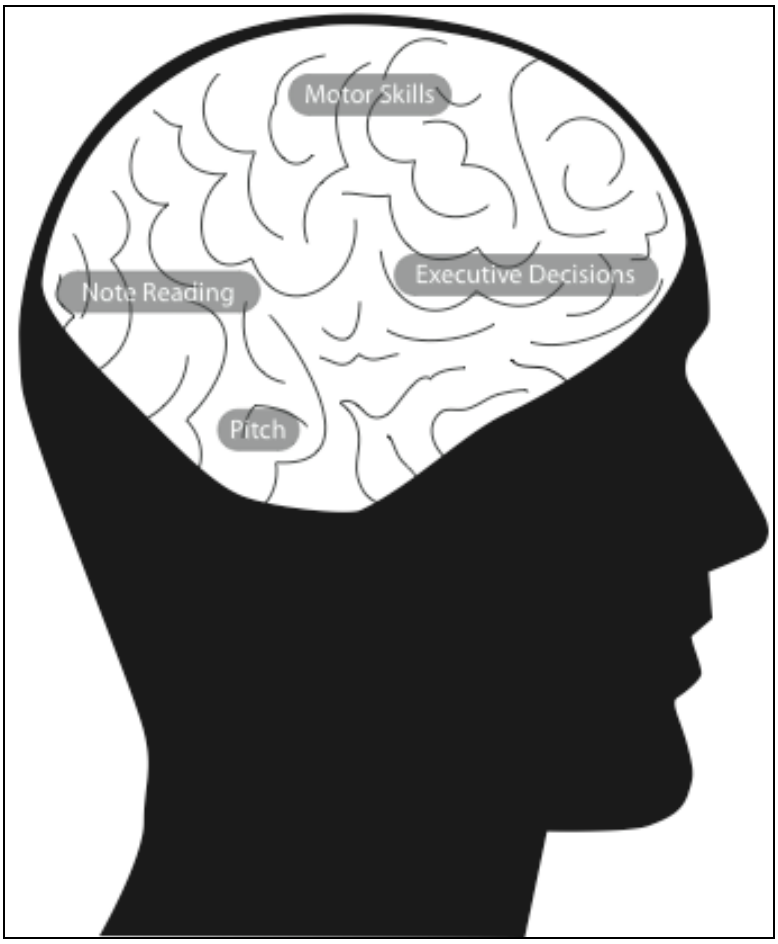



Figure 7. The Systems Level of a musical performance. Each neurophysiological system is responsible for a separate aspect of musical performance (e.g., rhythm perception, motor skills, or pitch recognition) based on the interaction of multiple neural networks (figure adapted from a sketch by the author).

*The Networks Level*

A neural network is a collection of similarly specialized neurons that fire together to create a distinct cognitive, motor, sensory, or emotional function. Thousands of neurons interconnect and interrelate to form hundreds of networks in a web of neural circuitry creating cortices for higher systems such as the auditory, visual, or motor cortex. Each collection of similarly specialized neurons that fire together contributes to one of an

organism's autonomic, perceptual, or cognitive functions, such as neurons that are specifically used for vertical lines of vision, others for motor skills with each muscle group, or others that are organized tonotopically (i.e., a hierarchy of neural areas in the auditory cortex that only respond to specific pitch frequencies). Figure 8 presents a conceptual model of some of the neural networks associated with piano performance.

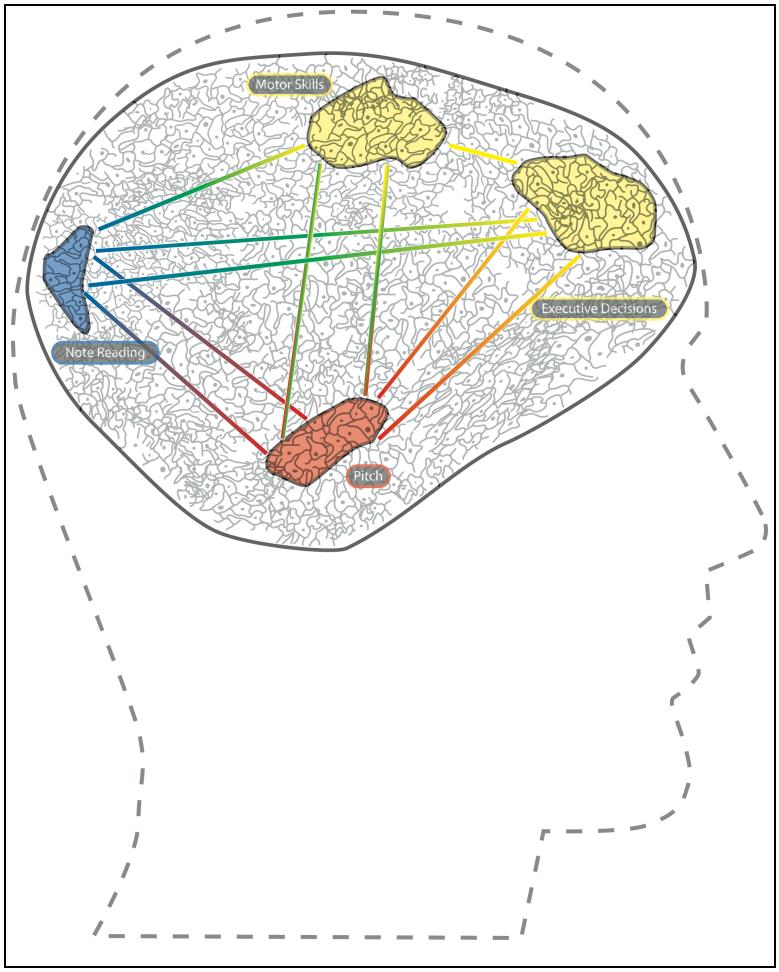



Figure 8. The Networks Level of a musical performance. Neural networks are groups of similarly specialized neurons forming connective circuits of axons and dendrites to share information with one another. A network is made up of thousands of neurons that are highly specialized for one task (e.g., nerve cells designated for pitch perception in the auditory cortex will only respond to a specific range of sound frequencies) (figure adapted from a sketch by the author).

Possible theories for a neurophysiological system of musical processing would likely be based upon several underlying neural subsystems that act cooperatively to form the whole of human musicality. These subsystems (or networks) may include neural circuits dedicated to specific elements of music like melody, harmony, rhythm, tempo, meter, duration, timbre, pitch recognition, intensity, or formal organization. Current brain imaging research identifying the activation of these musical subsystems is guiding neuroscientists to conclude that the neural substrates of music are widespread throughout both hemispheres of the brain, "with different aspects of music processed by distinct neural circuits" (Parsons 2001, p. 211).

Unlike other cells in the body, most neurons cannot reproduce. This is the reason stroke patients can have drastic difficulties recovering from a stroke because once a specialized region of the brain is destroyed, not only do those affected neurons die, but the specific behavior that they served may be lost as well. For example, when the composer Maurice Ravel (1875-1937) suffered a stroke in 1933, he damaged the neural pathways in his brain that were specifically associated with writing music (S. Johnson, 2004). Though Ravel retained the ability to hear and appreciate music, he was frustrated for the rest of his life by the loss of an ability to compose music. Brain damage studies such as Ravel's case strengthen the argument that musical processing is distinct from language systems.

Especially with adults, every neuron in the brain has a specific role to serve. Once neural pathways are lost it is very difficult for the adult brain to replace the lost specialized function associated with those neurons. Recent research in brain plasticity

has found that neurons neighboring damaged areas of the brain are able take over the lost functions, but this is more easily achieved with infants and young children than with adults (Drubach, 2000).

Regarding the specific identification of cognitive neural systems and networks in the cerebral cortex, Korbinian Brodmann (1868-1918) was one of the first to map how local neural networks and subsystems in the brain relate to higher-level systems and behaviors (McCaffrey, 2005). Over 50 Brodmann areas have been mapped out across the four lobes on either hemisphere of the cerebral cortex (Figure 9) and each Brodmann area references a different region of neural networks. Brodmann areas are frequently used in neuroscience to refer to the brain functions associated with specific regions of the cerebral cortex as described in Table 2.

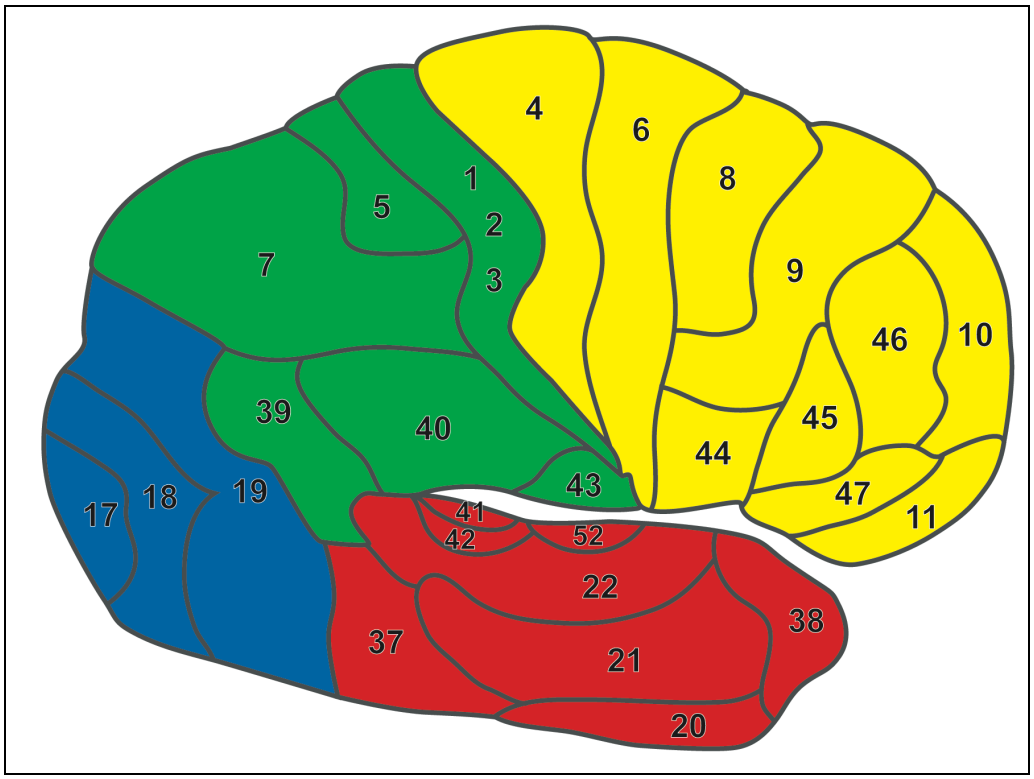



Figure 9. Sagittal brain view (i.e., side view) facing right of Brodmann's areas across four lobes of the cerebral cortex: (figure based on an illustration in Jonides, 2005).

Table 1.
Descriptions of Brodmann areas (McCaffrey, 2005).

| | |
|---|---|
| Occipital Lobe (*vision*) | Area 17: primary visual processing<br>Areas 18 & 19: secondary visual processing |
| Parietal Lobe (*somatosensory)* | Areas 1, 2, &3: primary sense areas of touch |
| Temporal Lobe (*auditory information*) | Area 41: primary auditory area (Heschl's gyrus)<br>Area 42: secondary auditory area |
| Frontal Lobe (*cognitive functioning*) | Area 4: primary motor area<br>Area 8: visual reflexes and pupil adjustments<br>Areas 9, 10, & 11: reasoning and judgment<br>Area 44: production of speech (Broca's area) |

*The Cellular Level*

Neurons possess two important common features: (1) they are strictly binary, meaning that a neuron either fires a signal down its axon to adjoining neurons' dendrites, or it doesn't (a.k.a., the "all-or-none" principle); and (2) with each synaptic firing or neurotransmitter reception, neurons encode information and are slightly modified (Stafford & Webb, 2005). This process of encoding information occurs at the cellular level where the axon of one neuron delivers an electrochemical message to the dendrite of other neurons (Figure 10). The efficiency and frequency of this neural communication is the basis of learning and memory. Known as Hebb's Rule, neural modification (i.e., learning) occurs in the following way:

> When an axon of (neuron) A… excites (neuron) B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells so that A's efficiency as one of the cells firing B is increased (Hebb, 1949).

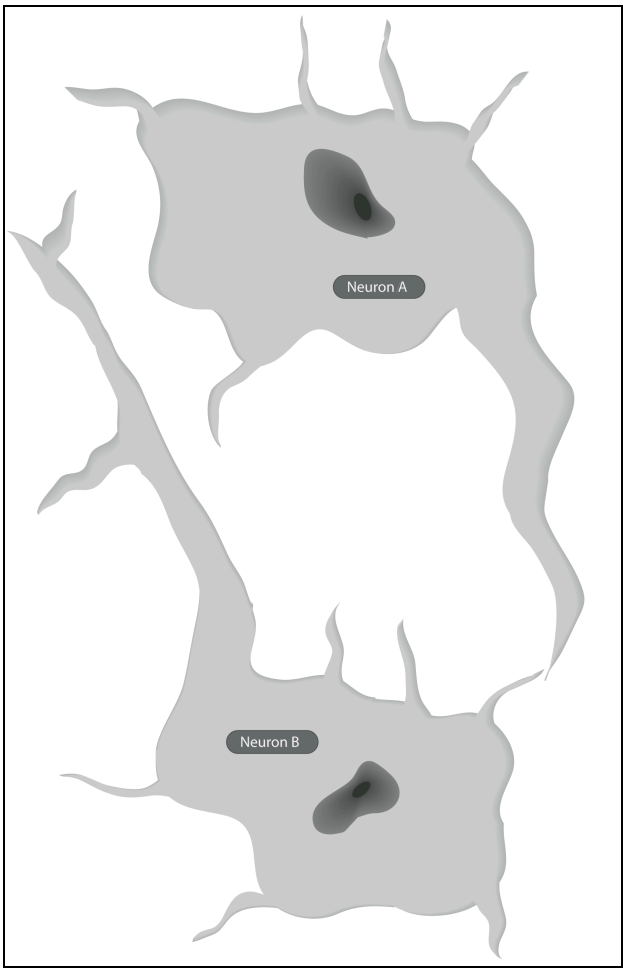



Figure 10. The Cellular Level of a musical performance. Each brain cell, or neuron, has one transmitting axon and hundreds of dendrites. The circled area depicts the synapse in which the axon of Neuron A transmits its electrochemical impulse to the dendritic receptor of Neuron B (figure adapted from a sketch by the author).

Excitatory neurotransmitters are specific kinds of chemicals that cause neural firing, as opposed to inhibitory neurotransmitters, which prevent neural firing (neurotransmitters will be explained in more detail in the *Synaptic (Molecular) Level* section). In the presence of excitatory neurotransmitters, the web of neural pathways that fire together is an important factor leading to cognitive action, but the frequency that a

neuron fires is also believed to play a role in the nature of neural computation. Neural firing frequencies can range from a few action potentials per second to several hundred per second (Churchland, 1993). To further complicate the matter, neural modification is based on several possible factors that occur as an original neural impulse is relayed via neurotransmitters down the synaptic pathway to other nearby neurons by the postsynaptic neuron (i.e., the neuron that receives a signal from the presynaptic firing neuron). These neural modification factors include:

1. The type of neurotransmitter used to fire a signal;
2. The amount of neurotransmitter released;
3. The rate at which the neurotransmitter is released by the presynaptic neuron and received by the postsynaptic neuron;
4. The interaction of other neurotransmitters released from nearby neurons;
5. How quickly the neural impulse is relayed down the synaptic pathway;
6. How close together the neurons are in proximity to each other; and
7. The order in which the presynaptic neurons release their neurotransmitters (Stafford & Webb, 2005).

Furthermore, the postsynaptic neuron will fire an electrical impulse down its axon to other neurons only when its dendrites have collected enough neurotransmitter molecules from other presynaptic neurons. Once the incoming neurotransmitter chemicals have raised the postsynaptic soma electrical potential to the requisite critical level (i.e., the threshold potential, or approximately 50 millivolts greater than the fluid outside the cell membrane) the action potential is reached and an impulse is fired down

the axon to another nearby neuron's dendritic receptor and the process begins again all along the neural pathway.

Myelin is an important component of neural development and many neuroscientists have proposed that the production rate of myelin is concurrent with higher order nervous functions (Shepherd, 1994). Shepherd even states that myelination is such an important neural structure that all nerve fibers are generally classified as unmyelinated or myelinated (1994, 59). The areas of the brain with myelinated nerve fibers are known as white matter due to the white color of myelin, as opposed to unmyelinated nerve fibers known as gray matter. Myelination facilitates higher order nervous functions by increasing the speed of neural communication. An unmyelinated axon transmits an impulse at a few meters per second, whereas a myelinated axon can send impulses up to 100 meters per second (Stillings et al., 1995).

Essentially, the faster that neurons can communicate with each other, the greater their potential for neural computation.

As a child grows, myelination is believed to play an important role in the acquisition of new behaviors and abilities. For example, babies may learn how to walk at about the same time (approximately 18 months) that the neural pathways of their motor cortex become myelinated. Some researchers suggest that the ability to talk coincides with the time when language areas around the auditory cortex become myelinated (Huttenlocher, 1979). With regard to the development of musical skills, perhaps myelination is responsible for research indicating that children as young as three and four

years old possess the ability to respond to tonality in musical stimuli (i.e., they are able to sing and stay in the key of a nursery song) (Dowling, 1988).

Suzuki teachers suggest that as pre-schoolers (ages 3-4) are developing their language skills, they are also capable of beginning instrumental music lessons (Slone, 1985), which perhaps not so coincidentally is the typical age, when myelination has spread to the visual, motor, and auditory cortex in most children. Whether or not the capacity for singing with tonality or controlling motor skills is directly tied to the development of myelination remains unclear and further research into the role of myelination in musical development is certainly warranted. While a diverse and enriching environment has been shown to promote neural pathway development during the first years of life (Bloom, Lazerson, & Hofstadter, 1985). Complete myelin development requires approximately 20 years to reach its maximum levels (Figure 11). Thus, by augmenting the rapidity and precision of neural communication across wide regions of the brain, myelination is one of the most important factors for higher order nervous system functions.

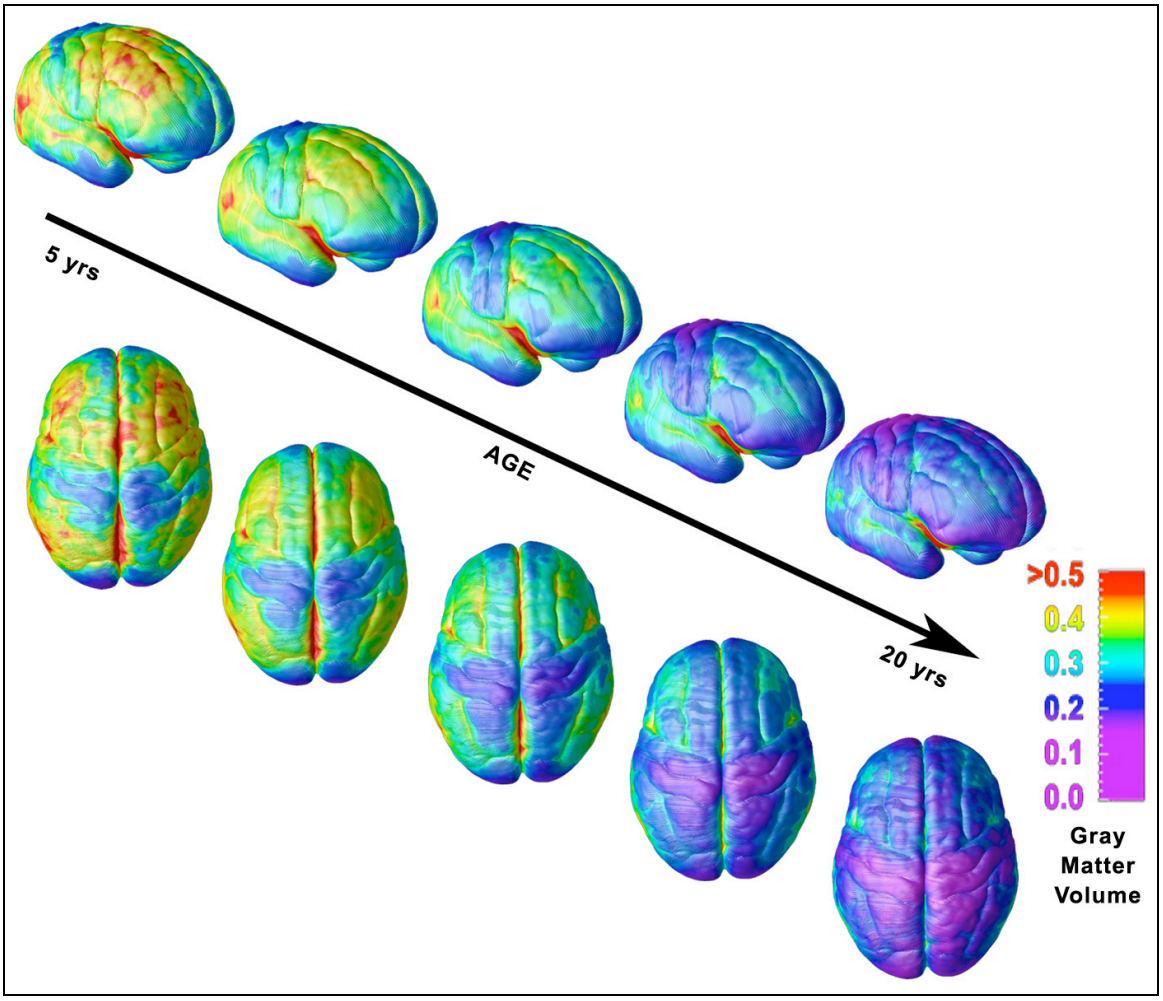



Figure 11. Average decreases in the percentage of gray matter volume from age five to twenty. The purple-violet areas arise with the decrease of gray matter volume and the increase of white matter due to myelination and synaptic pruning as the brain develops. Note that the myelinated areas at age five are primarily focused on the cerebral cortex lobes that correspond to age five abilities such as the occipital lobe in the visual cortex and the motor cortex in the parietal lobe (Gogtay et al., 2004) (reprinted with permission from Thompson).

*The Molecular (Synaptic) Level*

The point at which communication occurs between any two connecting neurons is known as the synapse. This is the place where neurotransmitter molecules travel between neurons sending electrochemical information from cell to cell (Figure 12). Beyond

genetic configuration, the nature of all CNS functions originates at the synaptic level based on the type and amount of chemical neurotransmitters that are used. A single neuron is capable of sending approximately 4,000 outgoing synaptic connections to other neurons (Shepherd, 1990), and anywhere from 100,000 to 200,000 incoming synaptic connections may be received by a single neuron from other neurons (Alkon, 1989). As each of the potentially forty quadrillion synaptic pathways is used repeatedly, its connections become stronger and more myelinated, thus increasing the speed at which impulses and neurotransmitters travel from one neuron to another.

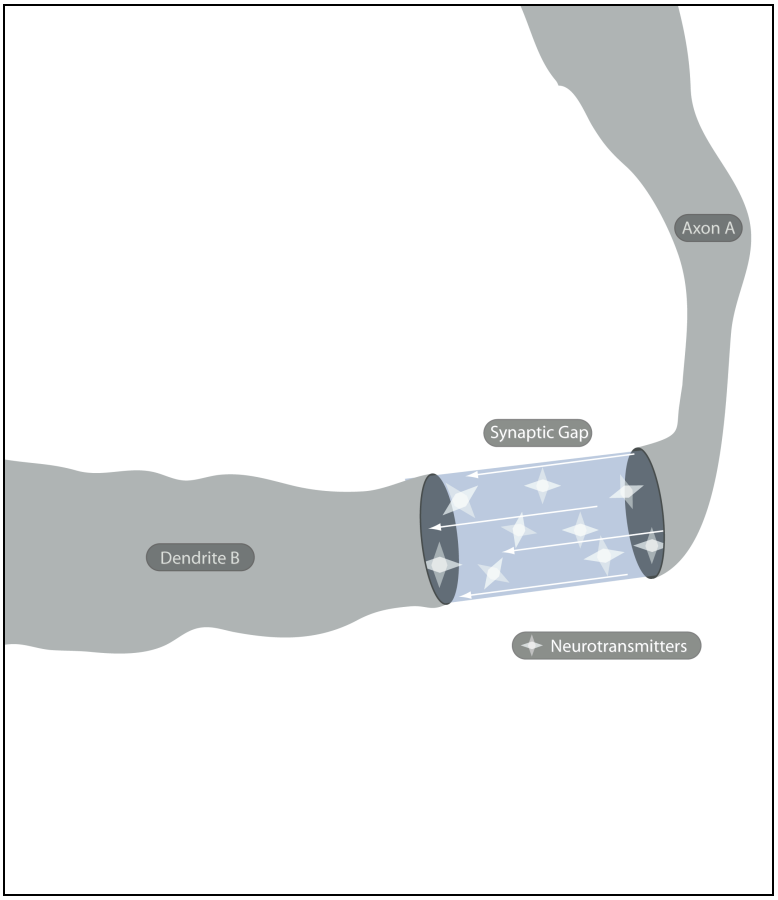



Figure 12. The Molecular (Synaptic) Level of a musical performance. Neurochemicals flow from the axonal transmitter, across the synaptic gap, and are collected by a neighboring neuron's dendritic receptor. In this figure, Neuron Y receives neurotransmitters from Neuron X, which are then deciphered into a neural message by the soma based on the type, frequency of transmission, and quantity of neurotransmitters used. This message is then relayed down the axon of Neuron Y via an electrical impulse that will transmit a similar neurotransmitter message to other neighboring neurons in the neural network.

The inverse of synaptic growth is neural death and synaptic pruning. The less a synapse is used, the weaker it will become. Synaptic pruning is a necessary part of neural growth in which either frequently used synapses thrive or unused synapses wither and die. Thus, the brain maximizes its efficiency by strengthening the neural pathways that

are most often needed, and closing the neural pathways that are unnecessary to the CNS. From this standpoint, an individual neuron that is disconnected or unused is practically useless since the computational components of the CNS are based on neurons working together to form systems and behaviors. Ultimately, neurons will die if they are not used regularly, especially in the early developmental stages of life.

At the molecular level of the brain, neurotransmitters serve as the basis for all nervous system communication between neurons. Over 50 different neurotransmitters have been identified that can either excite the flow of molecular information between neurons (i.e., excitatory neurotransmitters) or inhibit this flow (i.e., inhibitory neurotransmitters). Examples of neurotransmitters include glutamate, dopamine, serotonin, norepinephrine, and gamma-aminobutyric acid (GABA), each of which plays a primary role in thought processes and moods (Drubach, 2000).

As discussed above, there are several factors at play that determine how neurotransmitters affect neural modification (e.g., the quantity, proximity, or frequency of the neurotransmitters moving from one neuron to another). Despite the nearly infinite variations of neurotransmitter activity, there is a growing understanding for which mental states are associated with certain neurotransmitters. For example, neuropinephrine serves to regulate the reward-dependence of an organism upon pleasurable stimuli (S. Johnson, 2004) and the release of serotonin in the brain is associated with a sense of satisfaction for things that are comfortable or expected (Berns, 2005). Up until the mid 1990s, dopamine was thought to be the neurotransmitter commonly associated with pleasure; however, dopamine is currently believed to be more accurately associated with a sense of

novelty and newness, be it pleasure or pain (Nettle, 2005). From a philosophical perspective, some neuroscientists think that the role of dopamine may explain why happiness is fleeting as some people continually seek out new goals and experiences (Nettle & Berns, 2005).

The chemicals produced in the brain are not only involved, but are essentially responsible for every mood and cognitive function. The naturally produced drugs in the brain's chemistry are the means for neural communication, which in turn affect neural networks, systems, and ultimately, human behavior. Given the way that many people associate their moods with musical experiences, further research into the relationship between neurochemicals and music is warranted.

*The Genetic Level*

The total amount of DNA in an organism constitutes the whole of its genome. The genome for mammals is believed to consist of approximately 100,000 genes and the complexity of the brain is evident by the fact that more of the genes in a mammal are devoted to encoding proteins in the nervous system than in any other organ (Shepherd, 1994). Genes are responsible for encoding all organic cells with a genetic code serving as the blueprint for all cells in the body. When genes are passed on to other cells, gene expression is the process by which the genetic code is manifested into the new cells' physical form thereby affecting the potential capabilities of the expressed cells. The reason that children resemble their parents is because the parents' genes have been expressed in the children. Yet, genes are not the only determining factor for how cells

develop. As mentioned earlier, the status of each cell in the body can be attributed to a combination of environmental factors and predisposed genetic potential.

For example, while all humans may have the capacity to be musical, some people may have a greater genetic predisposition to process music. Early evidence of family traits for Absolute Pitch have been observed (Baharloo et al., 2000). Furthermore, there is a popular opinion that Mozart probably had a greater genetic potential for music processing than the average person; however, even Mozart's genetic musical traits would not have flourished if he had not been in an environment where those traits could thrive through musical exposure, training, and practice[1]. In the words of Robert Zatorre, director of the Montreal Neurological Institute and author of numerous neuromusical studies, musical ability is probably based on both a "bit of nature, a bit of nurture, like everything else" (Abbott 2002, p. 14).

## Brain Imaging Technology In Neuromusical Research

There are many different methods of measuring activity within the brain, but it wasn't until the invention of magnetic resonance imaging (MRI) that a non-invasive technique became available for viewing highly detailed images of the interior of living tissue (Kuperman, 2000). The idea of magnetic resonance imaging was first published in 1973 (Lauterbur) and by the 1980s, MRI had become the leading diagnostic tool in medical practice and research. In fact, the effect of MRI on science and medicine has been so significant that its leading developers, Paul Lauterbur and Peter Mansfield, both

[1] Mozart's father, Leopold, was recognized throughout Europe as the leading music teacher of his time (Levitin, 2006)

received the Nobel Prize for physiology and medicine in 2003.

In addition to neurological studies of brain damage or lesions, neuroscientists rely on a variety of neuroimaging techniques for measuring brain activity. Deciding which research tool to use depends on several factors including the degree of detail desired, the speed of an imaging device measuring a brain response relative to a stimulus, as well as a researcher's funding and training. For example, ERP and EEG (described subsequently) have the fastest measurement times in response to brain activity, while DTI and fMRI (described subsequently) have more detailed levels of measurement.

The number of discoveries about the brain connected with the types of technology listed below continues to grow every year. In the words of Rita Carter, author of *Mapping the Mind*, "As we enter the twenty-first century, functional brain scanning machines are opening up the territory of the mind just as the first ocean-going ships once opened up the globe" (1998, p. 6).

*Magnetic Resonance Imaging*

Also known as nuclear magnetic resonance imaging (NMR), this technology uses extremely powerful magnets to align the atomic particles within organic matter followed by exposure to radio waves. This process causes the magnetized particles to emit radio signals that vary according to the type of tissue that is present. Software analysis tools utilizing fast Fourrier transforms (FFT) convert the radio wave data into a three-dimensional picture of the inner body tissue.

*Functional Magnetic Resonance Imaging*

An advanced technique of magnetic imaging, functional Magnetic Resonance Imaging (fMRI) extends the technology of MRI by not only providing an inner 3D view of the brain, but by identifying the regions of greatest cognitive activity by showing the flow of oxygenated blood to activated areas of the brain (Kuperman, 2000). Blood flow in the brain responds approximately four to six seconds post-stimulus and as blood flows to a specific part of the brain due to an increase in neural activity, the fMRI reading identifies which blood-oxygen-level dependent (BOLD) regions are changing due to the stimulus.

Kuperman offered a more detailed explanation of how fMRI measures blood flow in the brain in the book *Magnetic Resonance Imaging: Physical Principles and Applications* (2000). He explained that increased blood flow in the brain coincides with an increase in oxygen supply that exceeds the increase in oxygen consumption. A temporary imbalance between the supply and consumption of oxygen is hypothesized to produce a decrease in the concentration of deoxyhemoglobin (i.e., blood that does not contain oxygen) relative to a predetermined resting state in the brain. "As a result, the susceptibility difference between blood and its surroundings also decreases, which in turn causes the observed increases in intensity" (Kuperman 2000, p. 64). The observable differences in the blood and its surroundings are usually so slight that statistical analysis of multiple scans is necessary to significantly differentiate between active and resting states in the brain.

*Positron Emission Topography*

Like MRI, Positron Emission Topography (PET) also identifies the areas of the brain that receive increased blood flow or metabolic activity, although its level of detail is not as great as fMRI (Carter & Frith 1998, p. 26). Brain activity is measured by tracking a radioactive substance such as water, glucose, or oxygen that has been inhaled or injected into a subject's bloodstream. Concentrations of the radioactive substance can be tracked as they flow into active brain regions (Herscovitch, 1994). Identifying the most active brain regions associated with a stimulus (e.g., performing on an instrument) is determined by paired-image subtraction in which the PET scan taken while a subject is engaged in a task is subtracted (differentiated) from the PET scan taken while the subject is alert, yet not engaged in any activity (Posner & Raichle, 1994).

*Electroencephalography*

Electrical patterns are created in the brain by the rhythmic oscillations of neural synaptic firing (Carter & Frith, 1998). Electrodes placed on the scalp of a subject can measure the electrical activity in the brain. The Electroencephalogram (EEG) is then mathematically analyzed using a fast Fourier Transformation (FFT) to divide the EEG into common frequencies: *delta* (0.5 - 4.0 Hz), *theta* (4.5 - 8.0 Hz), *alpha* (8.5 - 12.0 Hz), and *beta* (12.5 +Hz). Brainwave frequencies are a relative function of cognitive states (Kandel et al., 2000). EEG readings are very sensitive to interference and will foster artificial readings (artifacts) if the subject engages in an excessive body motion or even eye movement. For this reason, EEG studies do not usually incorporate active physical tasks and tend to measure listening or thinking activities.

*Event-Related Potentials*

Event-Related Potentials (ERP) allow a more precise measurement than the brain-wide perspective of EEG by associating a specific stimulus to the brain activity occurring at a specific point of time after the stimulus (e.g. 100 milliseconds) and then using computer analysis to average the EEG readings and cancel out the random aspects of the readings (Carter & Frith 1998, p. 26). ERPs use EEG mapping to average the electrical brain wave peaks (i.e., potentials) that are related to an internal or external stimulus (event) such as a spoken word or a musical note.

ERP readings consist of three main characteristics: (1) a positive or negative effect on the average EEG brain wave pattern, (2) the intensity level (amplitude) of this wave, and (3) the span of time that the occurs between the stimulus and the onset of the changed brainwave pattern caused by the stimulus. ERPs are categorized by the first and third of these characteristics such that a N100 ERP is a negative brain wave that occurs 100 milliseconds after the stimulus and P300 is a positive brain wave that occurs 300 milliseconds after the stimulus. Presented in order of their timing, there are several common types of ERPs associated with varying forms of mental activity such as concentration (N100), cognitive information processing (P300), and higher order perceptual processing (N400) (Arnadottis, 1990). In neuromusical research, ERPs of particular interest include N100, P300, and N400 (Hodges, 1996b).

*Magnetoencephalography*

This technique also detects neural oscillation signals, but unlike EEG, Magnetoencephalography (MEG) picks up the minute magnetic pulse of neuronal

oscillation rather than its electrical byproduct. Although the signal is not as strong as fMRI and interference is common, MEG is able to chart brain activities at a faster rate than any other measuring device (Carter & Frith 1998, p. 26).

*Transcranial Magnetic Stimulation*

In this procedure, a magnetic coil directs electromagnetic energy through the skull and into the brain, interfering with the normal function of localized brain cells without causing any permanent damage (Hilgetag, 2004). This technique allows researchers to map certain functions of the brain by temporarily disabling behavioral functions (e.g., hand tapping) and then identifying the specific regions of the brain that were affected by the magnetic interference. Essentially, Transcranial Magnetic Stimulation (TMS) is simulated brain damage, making some neuroscientists reluctant to use it in their research. Nonetheless, no harmful side effects have been detected to this point and TMS is currently being investigated by the U.S. Food and Drug Administration as a possible treatment for depression, obsessive-compulsive disorder, schizophrenia, Parkinson's disease, dystonia (involuntary muscle contractions), chronic pain, and epilepsy (Hilgetag, 2004).

*Diffusion Tensor Imaging*

One of the most recent developments in magnetic resonance imaging is Diffusion Tensor Imaging (DTI) which measures the self-diffusion, or random thermal motion of water in nervous tissue (DaSilva, Tuch, Wiegell, & Hadjikhani, 2003). Water molecules tend to move along the direction of nerve fibers. Thus, DTI is able to reveal the

orientation of nerve fibers within each voxel (i.e., a volume pixel, or the smallest observable space of a three-dimensional image).

## Theories and Models of Brain Processing

A recent review of neuroscience research reported that over 500 brain imaging studies are published in research journals every year and some neuroscientists are reluctant to admit their disappointment that there has not yet even been a definitive way to diagnose mental illness using brain imaging technology, let alone reach a conclusive model of brain processing (Carey, 2005). In an attempt to explain the limitations of neuroimaging, Michael Gazzaniga, founder of The Cognitive Neuroscience Society and current president of The Cognitive Neuroscience Institute, states that "hot spots" of brain scanning data are very different from person to person even for similar experiences and that such data are only appropriate for identifying the mental processes of the subject being measured (Gazzaniga, 2005). According to Gazzaniga, to infer that a single pixel of fMRI data active during a cognitive task with one subject could be generalizable to other subjects engaged in similar tasks is too specific an agenda for the current state of brain research. When considering the available data from imaging technology combined with the nearly infinite neural possibilities for the human brain to organize itself, the reader may get an idea of just how complicated a task it is to arrive at any theory of brain activity.

Despite this, theories and models of brain processes are carefully being put forward by neuroscientists to explain how all the cells and systems of the brain function together. Neuroscience *is* making progress for those who are patient enough to let

research take an objective course and consider all the data as it comes in. With new brain research every day, the models and theories presented below receive constant criticism and debate, but for the time being, these ideas have drawn interest for being the best available solutions to one of the most challenging questions in science: "How do humans think?"

*Triune Brain Model*

For more than thirty years, one of the most popular approaches for describing the structural organization of the brain has been the Triune Brain Model, proposed by Paul MacLean (1973). This model states that the brain consists of three distinct divisions that are categorized phylogenetically (i.e., relating to stages of evolutionary development). MacLean's theory is based on the relative neural function of each division and its place on an evolutionary timeline from oldest to newest in neural development: the *reptilian brain* (survival functions); the *paleomammalian brain* (emotional functions); and the *neomammalian brain* (rational functions) (Figure 13).

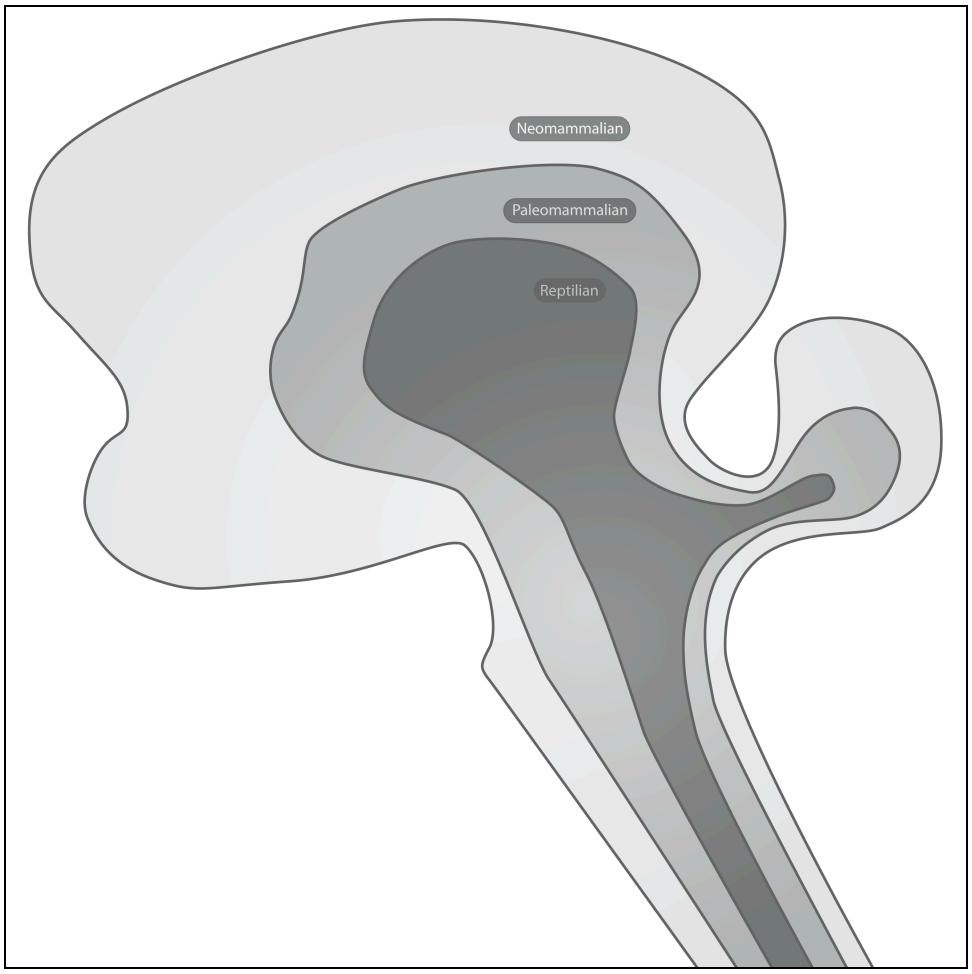



Figure 13. The Triune Brain Model.

Maclean's model describes the interrelated anatomy of the brain as the reptilian brain, the paleomammalian brain, and neomammalian brain which are comparable to the hindbrain, midbrain, and forebrain respectively. While current theories and models that are based on imaging research offer a more detailed explanation of brain anatomy, MacLean's model offers a general overview of brain processes and their corresponding regions.

*Hemisphericity*

Starting around the 1960s, a popular way to classify the origin of creative activities was to describe music and art processes to be generated in the brain's right hemisphere (RH), while language and logical activities such as math and science were said to originate in the left hemisphere (LH). These notions are often based on dichotic listening studies and neurological research observing the effects of brain damage with ensuing amusia (i.e., an inability to process music). Dichotic listening studies attempt to determine hemispheric dominance by presenting a subject with various auditory stimuli for up to two seconds and then measuring which cerebral hemisphere utilizes the greatest activation to process the incoming sounds. Auditory stimuli longer than two seconds are not used because these longer durations involve too much whole brain processing to assess any hemispheric dominance. This caveat should be addressed at the outset of any dichotic listening research review since most musical experiences take longer than two seconds to occur.

Data from numerous dichotic listening studies has shown that the left auditory cortex is dominant for the perception of verbal stimuli (Bryden, 1963; Kimura, 1967), while the right auditory cortex is dominant for the perception of nonverbal tonal stimuli (Blumstein, Goodglass, & Tartter, 1975; Kimura, 1964). Neurological case studies also support this hemispheric difference between the RH and LH (Hodges, 1996b, 212-216 presents a review of the effects of brain damage on musical behavior and 222-232 presents a review of dichotic listening research). In terms of music processing tasks located in the RH, and language or analytical tasks located in the LH, there is extensive

and sometimes contradictory evidence to support this notion but to report that music processing is strictly a RH activity would be highly disingenuous.

Perhaps the most intriguing element of dichotic listening studies exists in the research data showing that when subjects with musical training are engaged in music listening tasks, they are more likely have LH dominance (R. C. Johnson et al., 1977; Wagner & Hannon, 1981) or at least a lack of RH dominance (R. C. Johnson et al., 1977; Peretz & Morais, 1980; Selby, Rosenfeld, Styles, & Westcott, 1982). Though the evidence is contradictory, it appears that music processing may not be limited to just the RH, especially when training becomes a factor.

*Modularity and Connectionism*

Modularity refers to the theory that various brain processes from music and language to affective and regulatory systems are each controlled by distinct brain regions, or "modules". Some cognitive scientists prefer a more modular organization of the brain that is less hierarchically disjunct (e.g., the Triune Brain) for a model that is more concerned with the interrelated role that individual brain components have in all phases of life (Restak, 1994; Sylwester, 1995). Justine Sergent was one of the first neuroscientists to endorse the idea of widely distributed, yet locally specialized modules in the brain that are strictly dedicated to music processing (Sergent, 1993). Music processing modularity is strengthened by research showing that people with specifically localized brain damage may lose the capacity for music processing (i.e., amusia) without losing any other processes in the brain (Fries & Swihart, 1990; Peretz, Blood, Penhune, & Zatorre, 2001; S. J. Wilson, Pressing, & Wales, 2002).

Connectionism, on the other hand, is a brain theory based on a holistic view in which multiple areas of the brain cooperate together to serve the various functions of the brain. Several brain imaging studies are strengthening the argument for music processing occurring throughout the brain (Mazziota, 1988; Parsons, 2000; Parsons & Fox, 1997; Parsons et al., 2005). Further evidence in support of connectionism may come from research showing that as a listener shifts his focus among various elements of music processing (e.g., rhythmic, melodic, harmonic, or tonal elements) there is a corresponding shift in the intensity of brain activation across widespread areas of the brain (Parsons, 2001; Platel et al., 1997). As support for both modularity and connectionism continues to be found in neuromusical research, the possibility grows that both of these theories may be involved in music processing.

*Neural Networks*

As discussed in the section on neurophysiology, neural networks refer to the idea that similar types of neurons are grouped together to address each minutiae of brain activity. Some neuroimaging studies indicate the likelihood of musical neural networks for specialized processes such as identifying the scale structure of melodic passages (Janata et al., 2002) or by measuring the event-related potentials of tones that deviate from the expected scale degree (Besson & Faïta, 1995). The best evidence for neural networks that are unique to musical processing however, comes from neurological studies of brain damaged patients with amusia who have exclusively lost the capacity to recognize the musical domain while all other cognitive domains retain their ability to function normally (Peretz & Cotheart, 2003).

The determination of whether musical neural networks overlap with other processes (i.e., connectivity) or whether they are all distinct (i.e., modularity) remains unanswered. Some researchers conclude that neural networks for music may overlap with other neural components such as speech (Patel, 2003; Patel, Peretz, Tramo, & Labreque, 1998) or spatial reasoning (Hetland, 2000a, 2000b; Parsons & Fox, 1997; Shaw, 2000), while others hold that some musical neural networks are strictly dedicated to music only (Peretz & Morais, 1989; Peretz & Zatorre, 2005). Either way, the answer to whether one, both, or neither of these neuromusical camps are correct will have to wait because it is still too soon to conclusively explain how the neural gestalt of music processing occurs in the brain. With regard to the existence of a shared neural network between music and language, future neuroimaging studies are needed with music and language comparisons in the same experimental setting to measure the attentional focus of independent or cooperative processes (Shallice, 2003).

*Developmental Shifts*

Developmental shifts refers to the notion regarding "windows of opportunity" in a child's development when certain cognitive skills must be learned or else the opportunity to learn such skills would be lost forever. Optimal or cricital periods refer to the stages of neural development when a person is most ready to learn a new skill to his or her fullest potential, whereas the points before or after such periods are when a person's neural structure is either too underdeveloped or maturely structured to learn a new skill. For example, human babies possess the potential to learn any language on earth and speak it fluently as long as they are raised from birth amid the sounds of that language. By the

time adulthood sets in however, the neural pathways associated with language have become so reinforced that the nuances of other languages become much harder if not impossible to learn. This is a likely reason why native Japanese speakers have difficulty with l's and r's when speaking English due to the lack of these sounds in the Japanese language.

Developmental shifts are rooted in Piaget's theory for stages of development (1950) and the observation that at certain times in a child's life there are significant growth spurts in brain development (Epstein, 1978, 1986). Brain imaging studies by Flohr and Miller with EEG have discovered greater brain activity in 7 year olds engaged in musical experiences then when the children were 5 years old and engaged in the same musical experiences. Schlaug found that Absolute Pitch is more likely to develop in people who studied music before age 7 suggesting a window of opportunity for musical development (Schlaug, Norton, Overy, & Winner, 2005). Furthermore, differences in brain activity have also been observed between musically trained and nonmusically trained adult subjects of a similar age (Besson, Faita, & Requin, 1994; Fujioka, Trainor, Ross, Kakigi, & Pantev, 2004). These differences further support the theory for developmental shifts related to music processing.

As shown by Bloom and colleagues (1985), there is further evidence that synaptic growth flourishes when a subject is exposed to an enriched and stimulating environment. Researchers found that synaptic growth thrived in animals when they were raised in a stimulating environment (Greenough, 1984). Wild animals have even been found to have cortices that are up to one-third thicker than domesticated brethren. On the other hand, if

one grows up in an isolated and unstimulating environment, then synaptic growth is less likely to thrive. When animals are raised without a stimulating environment their synaptic growth is negligible. Several examples demonstrate this Hebbian condition.

For example, a study in neural development found that newborn kittens lost their ability to see out of one eye after the eye had been covered by a patch for several weeks (Hubel & Wiesel, 1970). Although the previously covered eye was healthy, the kittens were blind in it because the neurons in the kittens' brain for that eye had died off and were unable to process any incoming visual information. In other words, the Hebbian synapses in the kittens' visual cortex had withered and died through lack of use.

With humans, the case study of "Genie" (a pseudonum) is often cited as a tragic description of what happens when someone is raised without any nurturing or training (Curtiss, 1977). Discovered in 1970 by California social workers at the age of 13, Genie was forced to live in a locked shed. She weighed 59 pounds, was 4'6" and could not focus her eyes beyond 12 feet away. Why her mother chose to hide her away is unclear, but after a decade without normal stimulation or interaction, Genie lacked the basic behaviors and traits that most people would take for granted. By growing up in isolation she could not speak more than a few words, walk upright, or even use a toilet unassisted.

When Genie began to receive therapy she was able to make some improvements, but she was still severely limited in her ability to learn, quite possibly because of the drastic neural withering that her brain had undergone for most of her life. The physical trainer's adage of "use it, or lose it" applies to the brain as well as the muscles. In Genie's case, she missed her window of opportunity for developing normal social,

language, motor and visual skills because her neural pathways were never given the same opportunity to develop as other children her age. For optimum development, her case exemplifies that the greatest single purpose for any neuron is to regularly communicate and share information with other neurons in order to form a stronger network.

*Theories and Models Summary*

Given the variety of models and theories presented in this chapter, the exact nature of brain processing is still heavily debated despite the growing pool of brain imaging data. Perhaps the most important thing to recognize at this point is that brain processes are more likely based on a biological system of sympathetic relationships rather than the file storage and retrieval methods of a computer's operating system (S. Johnson, 2005; Shepherd, 1994; Sylwester, 1995).

If anything can be inferred at this point from the developments of neuroscience, it is that the human brain is a complicated yet consistently structured mechanism that can be widely varied in its synaptic organization from person to person based on genetic and environmental factors. Similarly, just as every human face has two eyes, a nose and a mouth, no two faces are alike.

A good analogy of the development toward theories and models of brain processing would be to consider the field of meteorology: although Doppler radar technology has vastly improved the ability of meteorologists to predict the biological patterns of weather, understanding weather on a global scale is still a highly complicated matter with many differing ideas. Likewise in neuroscience, imaging technology has

allowed the brain's functions to be more fully understood at the local, or reductionist level, but theories and models of overall brain processing are still inconclusive.

## Neuromusical Research Classifications of Related Literature

With an ever-expanding body of neuromusical research, current ideas leading to a musical brain model or theory may be revised, augmented, or perhaps even shown to be false. As studies were collected into the *MusicBIRD*, one of the stated research goals was to identify any themes consistently addressed across the body of research that may serve to establish a future model of music processing. Based on a review of neuromusical literature to this point, musical brain imaging research can be grouped into the following classifications: (1) *Perception and Cognition*, (2) *Affective Responses*, (3) *Musical Performance*, (4) *Memory and Learning*, (5) *Brain Plasticity and Neural Development*, (6) *Genetic Factors*, and (7) *Neural Correlates of Music Processing*. This section highlights findings in neuromusical research from each of these topics.

### *Perception and Cognition*

Perception is based on the sensory information that is gathered by the brain regarding one's external and internal environment. On the other hand, the highest order of nervous function draws upon memory, emotion, and cognition for complex thought processes (Shepherd, 1994). To date, the majority of neuromusical research has focused on music perception since most of the musical stimuli measured thus far with human subjects are no more advanced than a musical phrase (Peretz & Zatorre, 2005). Before observing something as complicated as music at the cognitive level, many researchers

have acknowledged the initial investigative value of using a bottom-up approach whereby each element of music processing is studied separately (Zatorre & McGill, 2005). As discussed earlier in Chapter I, the general idea of this reductionist approach is that by studying the specific neural activity of music processing's discrete components (e.g., pitch, rhythm, or timbre), the foundation will be set for future studies to explore the gestalt of these discrete components in holistic musical experiences.

But identifying music's discrete components with a reductionist approach presents an intriguing dilemma because some of these components may be strictly delegated to the processing of music (e.g., melodic pitch relationships or metric rhythm patterns), while other components such as long-term memory are activated by multiple cognitive systems. Thus, in the current review of neuromusical perception studies, it is important to recognize that conclusions are frequently based on brain activations in response to a discrete musical element (e.g., pitch or rhythm) and not a holistic musical experience. For example, several neuroimaging studies support the common observation that right hemispheric regions are engaged in the perception of pitch (Kohlmetz, Muller, Nager, Münte, & Altenmüller, 2003; Kuriki, Isahai, & Ohtsuka, 2005; Peretz & Zatorre, 2005; Schneider et al., 2005; Shahin, Bosnyak, Trainor, & Roberts, 2003; Warrier & Zatorre, 2004) and that left hemispheric regions are engaged in the perception of rhythm (Bengtsson & Ullen, 2006; Di Pietro, Laganaro, Leemann, & Schnider, 2004; Schneider et al., 2005; Vuust et al., 2005). This evidence, however, only offers an informative insight into *part* of the human musical experience.

The entirety of music processing is much more complicated than an examination of the brain's hemispheres or localized parts, an idea that has been strengthened in the last few years by neuroimaging studies revealing widespread bilateral brain activity during discrete music processing tasks (Bunzeck, Wuestenberg, Lutz, Heinze, & Jäncke, 2005; Kristeva, Chakarova, Schulte-Mönting, & Spreer, 2003; Kuck, Grossbach, Bangert, & Altenmüller, 2003; Lo & Fook-Chong, 2004; Lo, Fook-Chong, Lau, & Tan, 2003; Popescu, Otsuka, & Ioannides, 2004; Satoh, Takeda, Nagata, Hatazawa, & Kuzuhara, 2003) and even some cases of more holistic musical experiences (e.g., piano performance of Bach) (P. Fox et al., 1995; Parsons, 2001; Parsons et al., 2005). Yet more data is needed, especially for generative holistic musical experiences such as composition and improvisation.

The available neuroimaging research of both discrete and holistic musical experiences is still too limited to make many strong conclusions about the nature of music processing and whether it is (a) specifically localized to distinct neural networks (i.e., modularity), (b) made up of shared neural networks that are associated with other brain processes (i.e., connectionism), or (c) perhaps a hybrid of both of these theories. Recent studies addressing the level of music processes have explored the possibility of connections between music and language processing (Koelsch et al., 2003; Koelsch et al., 2004; Levitin & Menon, 2003; Ross, Olson, & Gore, 2003; Saffran, 2003; Schon, Magne, & Besson, 2004), or the role of brain regions mediating pleasure, autonomic and cognitive processes which contribute to the enjoyment and ubiquity of human musical experiences (Khalfa, Schon, Anton, & Liegeois-Chauvel, 2005; Menon & Levitin, 2005).

Another important observation is that brain activation sites can be altered in response to changes in three variables: musical stimuli (e.g., "real" music as opposed to MIDI-generated chord sequences, or even less realistic pure tones), tasks (e.g., holistic listening versus discrete features detection), and subjects (e.g., trained versus untrained). For example, musical training appears to increase the areas of brain activation during music processing (Cui et al., 2005; Koelsch, Fritz, Schulze, Alsop, & Schlaug, 2005; Schneider et al., 2005; Seung, Kyong, Woo, Lee, & Lee, 2005) as well as increase the efficiency of brain activity during musical tasks (Haslinger et al., 2004; Meister et al., 2005). Furthermore, while most people regardless of their musical experience are able to identify deviations from expected melodic, harmonic, and rhythmic outcomes (i.e. mismatched negativity), musically trained individuals appear to have an enhanced ability to detect these musical deviations (Besson et al., 1994; Fujioka et al., 2004).

Pitch Analysis

Although there is some evidence showing that certain types of pitch perception involve areas other than the right hemisphere (e.g., the brainstem) (Gulick, Gescheider, & Frisina, 1989), multiple neuroimaging studies have consistently observed that the right secondary auditory cortex is an area highly involved in various types of pitch processing such as frequency and amplitude modulation (Hart, Palmer, & Hall, 2003), spectral alterations (i.e., timbre changes) (Hall et al., 2002; Thivard, Belin, Zibovicius, Poline, & Samson, 2000), and fine-grain pitch responses (Zatorre & Belin, 2001). Fine-grain pitch analysis (i.e., the ability of the auditory cortex to discriminate subtle changes in pitch and timbre) is probably more important to music processing than to any other system domain,

including language (Peretz et al., 2002; Zatorre, Belin, & Penhune, 2002). Finally, studies of simultaneously sounded pitches indicate that harmony engages both hemispheres during music processing (Koelsch et al., 2002; Koelsch & Mulder, 2002; Maess, Koelsch, Gunter, & Friederici, 2001).

Temporal Analysis

Unlike pitch, temporal grouping processes (i.e., rhythmic processes) commonly occur in the left hemisphere. Even before neuroimaging data was available, behavioral evidence had long implied a rhythmic dominance in the left hemisphere due to the observation that it is easier to tap a complex, syncopated rhythm with the right hand than with the left (Ibbotson & Morton, 1981). More recent findings have confirmed the left hemispheric dominance of temporal grouping through neuroimaging studies of rhythmic tapping exercises (Sakai et al., 1999) and brain lesion studies (Liégeois-Chauvel, Peretz, Babai, Laguitton, & Chauvel, 1998) as well as identifying the involvement of the cerebellum in rhythmic awareness (Janata & Grafton, 2003). Finally, while the perception of rhythm is processed in the left hemisphere, metric grouping processes (i.e., perceiving a beat) are located in the right hemisphere (Liégeois-Chauvel et al., 1998; Penhune, Zatorre, & Feindel, 1999) further strengthening the argument for holistic music processing occurring throughout the brain.

*Affective Responses*

For the average music lover, emotional responses to music are often cited when people attempt to describe why they value music. In musicology, philosophical investigations of emotion have produced several famous treatises on this complex

relationship (Langer, 1967; Meyer, 1956; Reimer, 1989). Yet until the last decade, emotion and music has not received as much attention as other classifications of neuromusical research, especially perception.

The measure of affective behaviors is a difficult task given the subjective nature of emotional material. Even imaging studies investigating the brain responses of music listening to "happy" or "sad" music should be carefully interpreted based on the idiosyncrasies that each person might apply to a musical experience. The evidence is still limited and contradictory, however, when the idiosyncratic differences of each subject are taken into account during neuromusical imaging emotional response studies, some researches report that the distinctness of the brain activation areas associated with what a subject deems to be happy or sad music listening conditions are vaguely dissociated from each other (Kreutz, Russ, Bongard, & Lanfermann, 2003; Panksepp & Bekkedal, 1997) whereas others have found that joyful and happy music produces left hemisphere activity while sad and fearful music produces right hemisphere activity (Schmidt & Trainor, 2001).

Music is known to have a wide range of physiological effects on the human body including changes in heart rate, skin conductivity (i.e., the "chills-down-the-spine" effect), respiration, blood pressure, muscle tension, skin temperature, and biochemical responses (Bartlett, 1996). While emotional response is an area of neuromusical research in greater need of study, perhaps the most intriguing evidence thus far is the association that music processes have with the activation of pleasure areas in the brain (Khalfa et al., 2005; Menon & Levitin, 2005). Furthermore, investigations of skin conductivity have

even revealed that the "chills effect" associated with extremely pleasing music activates areas of the brain believed to be involved in the regulation of reward and motivation.

The musical activation of areas involved in mediating biological responses for rewarding stimuli (e.g., food or sex) is sparking new interest in emotion research because music appears to connect the rational parts of the modern brain with the survival-based systems of the primordial brainstem (Blood & Zatorre, 2001; Zatorre & McGill, 2005). Of course, it is too soon write a theory of why music engages these emotional systems, but perhaps the importance that music has achieved among humans is based on the way it appeals to both our feelings and our intellect.

*Music Performance and Neuromotor Tasks*

Beyond its auditory elements, music performance is also an intensely physical process such that experienced musicians have been referred to as small-muscle athletes for the fine motor skills that they develop in comparison to the large muscle specializations of professional athletes (F. Wilson, 1986). The fronto-parietal junction contains a sensory-motor cortex that is responsible for interpreting incoming sensory information and controlling the muscles throughout the body. In conjunction, the basal ganglia works to control large groups of muscles in cooperative functions and the cerebellum helps to regulate intricate muscle movements as well as storing habituated motor patterns. As mentioned previously, the brain is very plastic and with repetitive training, the brain's homunculus (i.e., sensory-motor map) is highly reorganizable (Kaas, 1991).

The way that music processing affects the motor cortex has been explored through several studies within the expressive cognitive mode. Not only is the motor cortex activated by piano performance (P. Fox et al., 1995; Parsons et al., 2005), but also mental rehearsal of a piano exercise activates the same motor cortex areas as performing the actual piano exercise (Pascual-Leone et al., 1995). Furthermore, long-term musical training has been found to increase the area of the motor cortex responsible for controlling the fingers of violinists (Elbert et al., 1995) and pianists (Meister et al., 2005).

*Memory*

The experiences of life have the potential to be stored in the brain in two ways: working (i.e., short term) memory and long-term memory. Investigations into the forms of musical working memory indicate that pitch recognition and tonal memory engage the right auditory cortex (Zatorre & Samson, 1991) and areas of the frontal cortex (Gaab, Gaser, Zaehle, Janäcke, & Schlaug, 2003; Holcomb, Medoff, Caudill, Zhao, & Lahti, 1998). Based on these findings, musical working memory may be a specialized subsystem of general working memory (Marin & Perry, 1999).

In terms of long-term musical memory processes (e.g., recognizing familiar melodies) activation of the frontal cortex and left inferior temporal lobe is a key difference from musical working memory (Platel, Baron, Desgranges, Bernard, & Eustache, 2003; Platel et al., 1997). Using musical imagery has been a useful method of measuring long-term musical memory by taking brain scans of subjects as they imagine (but do not hear) a familiar tune. Apparently, mental imagery accesses the perceptual systems that are involved in music processing as demonstrated by activations of the

secondary auditory cortices during imagined melodic rehearsals (Halpern & Zatorre, 1999; Zatorre, Halpern, Perry, Meyer, & Evans, 1996) tonal sequences (Penhune, Zatorre, & Evans, 1998; Yoo, Lee, & Choi, 2001) or even just isolated pitches (Halpern et al., 2004). Auditory cortex activity despite the absence of acoustical stimuli suggests that auditory perceptual mechanisms are involved in the subjective experience of musical memory (Peretz & Zatorre, 2005). In other words, two people might listen to the exact same performance and yet, based on the unique musical organization of their brains, they could remember their perception of the performance in completely different ways.

*Plasticity*

The anatomy and physiology of the brain is affected by a person's experiences throughout life (Stiles, 2000). The ability of the brain's morphology to change over time is known as plasticity and these changes can occur either by positive influences (e.g., learning and training) or by negative influences (e.g., injury and illness) (Nelson & Bloom, 1997). For example, when one area of the brain is damaged, a nearby area of the brain is sometimes able to take over the neural responsibilities of the damaged area (Drubach, 2000). Conversely, as learned behaviors are conditioned by training, the structures of the brain associated with a given task may increase in size. Evidence of this positive plasticity with musicians has been observed in various brain structures such as the auditory cortex (Levitin & Bellugi, 1998; Pantev et al., 2001; Schlaug, Jäncke, Huang, & Steinmetz, 1995), the corpus callosum (Schlaug, 2001; Schlaug, Jäncke, Huang, Staiger, & Steinmetz, 1995) and the motor cortex (Elbert et al., 1995; Meister et al., 2005; Pantev et al., 2001; Schlaug, 2001).

*Learning and Neural Development*

As addressed earlier, synaptic connections in the brain strengthen with repeated use leading to plastic changes in brain morphology. The effect of music processing on brain development has been an area of interest to both neuroscientists and music educators. For example, four-year old children engaged in daily classical music listening activities for six months were found to have significant increases in brain activity as compared to controls (Maliarenko et al., 2003). Also, four-year olds receiving Suzuki training had greater auditory responses to tonal stimuli than untrained children (Trainor, Shahin, & Roberts, 2003). Children aged four to six who have received musical training exhibited EEG patterns during music listening activities suggesting increased cognitive activity and greater relaxation than untrained children (Flohr, Persellin, & Miller, 1996).

In comparisons of musically and nonmusically trained individuals, musical training does not seem to have an effect on discriminations between pleasant and unpleasant music (Makris & Mullet, 2003). Furthermore, while most people regardless of their musical experience are able to identify deviations from expected melodic, harmonic, and rhythmic outcomes, musically trained subjects appear to have an enhanced ability to detect these musical deviations (Besson et al., 1994; Fujioka et al., 2004).

*Genetic Factors*

While music processing may be a common trait within the potential of all humans, the extent of a person's musical capacity is not simply based on a *tabla rasa* in which everyone learns to be musical from the same blank slate. Although every brain has the same basic anatomy, the complex interaction of nature and nurture (i.e., genetic

expressions and environmental experiences) combine to produce the unique neural organization of each human brain (Oerter, 2003). Determining the exact degree of influence from these varying factors is what remains unknown.

The development of Absolute Pitch (AP) is one example of music processing that seems to be determined by both genetic and environmental influences. Research showing that AP is a hereditary trait (Baharloo et al., 2000; Drayna, Manichaikul, de Lange, Snieder, & Spector, 2001; Gregersen, Kowalsky, Kohn, & Marvin, 2000) is balanced by evidence that explores the effect of musical training on the development of AP (Takeuchi & Hulse, 1993; Ward, 1999; Zatorre, 2003). Additionally, research into extreme degrees of congenital amusia or musical savants may enhance the understanding of genetic factors for musical development. Congenital amusia refers to genetic defects that prevent normal music processing (Peretz et al., 2002), whereas as musical savant is someone with exceptional musical talent in conjunction with some other cognitive deficiency or mental handicap (L. Miller, 1989).

*Neurophysiological Relationships to Music*

Responses to music that change the body's chemistry have been of great interest in the medical field for the therapeutic benefits that musical experiences elicit in recovering patients. A small but intriguing body of research suggests that musical experiences with imagery strengthens the immune system by promoting the release of stress reducing biochemicals such as interleukin-1 (Bartlett, Kaufman, & Smeltekop, 1993), or by controlling the release of stress related biochemicals such as cortisol (Tanioka et al., 1987) and immunoglobulin A (Tsao, Gordon, Maranto, Lerman, &

Murasko, 1991). Music therapy is also identifying very successful treatments for alleviating pain in patients, reducing the time required for recovery, and reducing the drug dosages by up to 50 percent (Spintge & Droh, 1992).

Music's effect upon the release of neurotransmitters in the brain is gaining interest as well. Recall from the molecular level section of neurophysiology that serotonin is a neurotransmitter commonly associated with feelings of satisfaction from expected outcomes, and dopamine is associated with feelings of pleasure based on novelty or newness. In a study measuring the neurophysiological responses of pleasant and unpleasant music, serotonin levels were significantly higher when subjects were exposed to music that they found pleasing (Evers & Suhr, 2000). Another study with subjects exposed to pleasing music found that dopamine levels increased while connectivity between areas of the brain responsible for mediating reward, autonomic, and cognitive processes was observed (Menon & Levitin, 2005). Even rats with hypertension were able to reduce their blood pressure and increase their dopamine levels when they were exposed to Mozart (Sutoo & Akiyama, 2004).

### *Neural Correlates of Music Processing*

#### Language

The left planum temporale was identified in Chapter I to be an area of the auditory cortex that is significantly larger in the brains of musically trained individuals. Many neuroscientists recognize the PT as a structural marker of left hemispheric language dominance (Schlaug, 2001) and the left PT has also been observed to have a functional dominance during story listening (Tzourio, Nkanga-Ngila, & Mazoyer, 1998).

The relationship between language and music processing has been debated among many specialists from evolution to linguistics, but this discussion can also be valuable to music teachers who are seeking effective ways to communicate musical experiences to their students. Research in music education has alluded to this relationship between music and language via experimental studies in the use of instructional modeling.

For example, music teachers who use modeling during instruction (i.e., providing a musical example rather than a verbal description) have been found to be more effective at communicating how to improve student music performance than music teachers who use modeling with verbal instruction, or just verbal instruction (Rosenthal, 1984). The effectiveness of modeling in music instruction has been reinforced by other studies as well (Byo, 1990; Haack, 1972; Jetter & Wolff, 1985; Sang, 1987).

Although music modeling does not have a direct connection to language communication, considering these behavioral music education studies with Schlaug's research does open questions about the relationship between music and language. Given that (a) modeling is an effective form of music teacher communication, and (b) a part of the brain enlarged by musical training (the left PT) is also involved in language comprehension, then there is justification for further neuromusical exploration into the relationship between music and language processing.

Academic Achievement

As stated earlier, Hodges and O'Connell (2005) report that there is not a clear indication for music processing having a relationship with academic achievement due to extensive contradictory evidence. At present, there are numerous studies showing that

music processing and academic achievement do not share a strong relationship (Barrett, 1993; Drennan, 1984; Duke, Flowers, & Wolfe, 1997; Haynes, 1982; Hobbs, 1985). On the other hand, there are also several cases of research showing that this relationship might actually exist.

For example, positive relationships have been observed between students who receive music instruction and measurements of reading ability (Butzlaff, 2000), mathematical skills (Vaughn, 2000), or verbal memory (Chan, Ho, & Cheung, 1998; Ho et al., 2003; Jakobson, Cuddy, & Kilgour, 2003; Kilgour, Jakobson, & Cuddy, 2000). Positive correlations were also found between students receiving exemplary music instruction and math and English test scores (C. M. Johnson & Memmott, 2006), instrumental sight-reading scores and grades in reading, math, and overall GPA (Ciepluch, 1988), as well as the observation that students receiving music instruction were found to be positively associated with intelligence tests measuring enhanced spatial-temporal abilities (Hetland, 2000a), and visual-motor integration (Orsmond & Miller, 1999).

The behavioral evidence for the neural correlates of music processing, however, does not have much neuroimaging data to strengthen its position. Except for a few cases identifying common brain activations in music and mathematical processes (Schmithorst & Holland, 2004) or spatial intelligence tasks (Jausovec & Habe, 2005), there is little neuroimaging research investigating the connections between music processing and academic achievement. Furthermore, many neuroscientists agree that the only conclusive evidence identifying a connection between musical and nonmusical brain processes will

stem from longitudinal studies comparing the neural development and behavioral data of musically trained subjects versus non nonmusically trained subjects from early childhood up to adulthood (Hodges, 2000b; Schlaug et al., 2005).

Spatial Intelligence

The idea that musical and spatial intelligence are proximal (i.e., sharing similar systems in the brain) and that music acts as a highly structured mathematical realization was proposed as the Trion theory by Gordon Shaw (Leng & Shaw, 1991). The Trion theory served as the basis for research leading up to the "Mozart Effect" ® which received popular press in the mid-1990s for the increase in spatial intelligence that was observed immediately after subjects listened to a recording of Mozart (Rauscher, Shaw, & Ky, 1993) or received music instruction (Graziano, Peterson, & Shaw, 1999). Despite this early evidence for increasing nonmusical intelligence through musical experiences, reproduction of the "Mozart Effect"® has been inconsistent for other researchers (Steele, Brown, & Stoecker, 1999) and some researchers have identified cognitive domains other than music that may have a stronger relationship with spatial intelligence (e.g., visual rhythm tasks) (Lints & Gadbois, 2003).

In the future, brain imaging studies have the potential to uniquely investigate the relationship between music and non-music processes by more clearly showing whether or not music processing activation regions in the brain correlate to other forms of non-music processing such as language, mathematics, or spatial reasoning. Not many researchers have utilized brain imaging technology to explore the musical-academic link. The lack of brain imaging data in this area is an indication of one direction that neuromusical

research could take, such as Pantev and his colleagues are currently doing with a longitudinal magnetoencephalography study to document the brain morphology and cognitive development of young musicians (Abbott, 2002).

## Conclusion

On the whole, a solid grasp of neuroanatomy and neurophysiology will be necessary to effectively evaluate the extant brain imaging neuromusical research, and in turn, infer any pedagogical, psychological, or philosophical insights for music education. It should be noted that the idea of general advancement through an understanding of the brain is not a new idea. Just as Freud's study of the mind widely affected twentieth-century psychology in a variety of fields from education to advertising, modern neuroscience may have just as wide an effect on life during the twenty-first century.

Given the evidence for musical hemisphericity, modules of music processing, or music processes based on the connectivity of disparate networks and systems, possible explanations for the whole of human musicality may be based on (1) a balance of rational, creative, and emotional processes throughout the forebrain, midbrain, and hindbrain, (2) the neural overlap of music and other systems such as language or spatial reasoning, (3) a system of neural modules in the brain, each of which handles a specific element of music processing, or (4) some other unknown neuromusical quality that is yet to be determined. As stated repeatedly, further research is abundantly warranted to address these questions.

Whatever the reason for the existence of music, one should not lose sight of the nearly infinite neural connections that the human brain can arrange for itself. Howard

Gardner, who proposed that music processes are one of nine different forms of human intelligence, put it this way: "…The various ways in which music can be processed cortically probably reflect the wealth of ways in which humans have found to make and absorb music" (1983, p. 119). Perhaps the reason that music is so intriguing to humanity is simply because it is too complicated a process to be identified the same way in each person. On the other hand, if music processes are inconsistent from person to person, then why is music so ubiquitous throughout human history? If ever there will be a way to discover the origins of music or the basis of music cognition, then brain imaging research is the best tool currently available to potentially offer an answer to these questions.

# CHAPTER III

# PROCEDURES

## Restatement of the Research Purpose

Given the advent of brain imaging neuromusical research, in conjunction with a lack of holistic efforts to tie these studies together, there is a clear need to organize neuromusical research into a summative database. At this time, no such resource exists. The guiding principles of this dissertation will be to (1) assess and clarify the current state of neuromusical research, and (2) explore how this research relates to the pedagogical, psychological and philosophical foundations of music education.

## Sources of Data

The principal research procedure for this study was to identify brain imaging studies involving human music processing published in peer reviewed research journals. The articles included in the *MusicBIRD* were selected from all neuromusical studies published by December 31, 2006 as identified in keyword searches for "music" and "brain" across four prominent research databases covering biological sciences (*PubMed*), social sciences (*PsycInfo*), music research (*RILM*), and educational research (*ERIC*).

## Qualifying Parameters for *MusicBIRD* Article Selection

All articles entered into the *MusicBIRD* employed the use of some form of imaging technology to investigate a neuromusical event or condition. The keyword

searches to identify music related brain imaging studies yielded hundreds of articles, many of which did not fulfill a consistent definition of neuromusical research. For the purposes of this dissertation, neuromusical research fulfilled at least one of the following conditions:

1. Auditory perception (i.e., sub-conscious awareness) or cognition (i.e., conscious awareness) of complex tone musical processes (e.g., pitch, timbre, melody, harmony, rhythm, timbre, phrasing, formal music structure, performance, reading or writing notation, or composition).

2. Mental imagery of music processing (i.e., audiation, or imagining musical processes).

3. Subjects performing multiple tasks (e.g., reading, talking, and singing) to compare neuromusical correlates (i.e. the relationship between neural networks dedicated to musical and nonmusical tasks).

4. Comparisons of musically and nonmusically trained subjects.

On the other hand, research that will not be included in the *MusicBIRD* may be for any of the following reasons:

1. Lack of human subjects. For example, many researchers have associated the brain processes associated with bird songs such as the study "Topographic representation of periodicities in the forebrain of the mynah bird: one map for pitch and rhythm?" by Hose, Langer, and Scheich (1987).

2. Lack of new brain imaging data (e.g., articles that are written as a review of other researchers' studies and do not present any original neuromusical imaging findings may also be omitted from the *MusicBIRD*. An example of this type of study is "Subcortical neural coding mechanisms for auditory temporal processing" by Frisina (2001).

3. Use of music processing as one of several human tasks to investigate imaging technology methods rather than to further the understanding of brain processes. An example of this type of study is "Improved auditory cortex imaging using clustered volume acquisitions" by Edmister, Talavage, Ledden and Weisskoff (1999).

4. All non-English studies without an available translation may be omitted. However, when translations are available, the *MusicBIRD* title field will contain the translated title in brackets in the following way: [Functional MRI of human brain in musicians and non-musicians] (Cui et al., 2005).

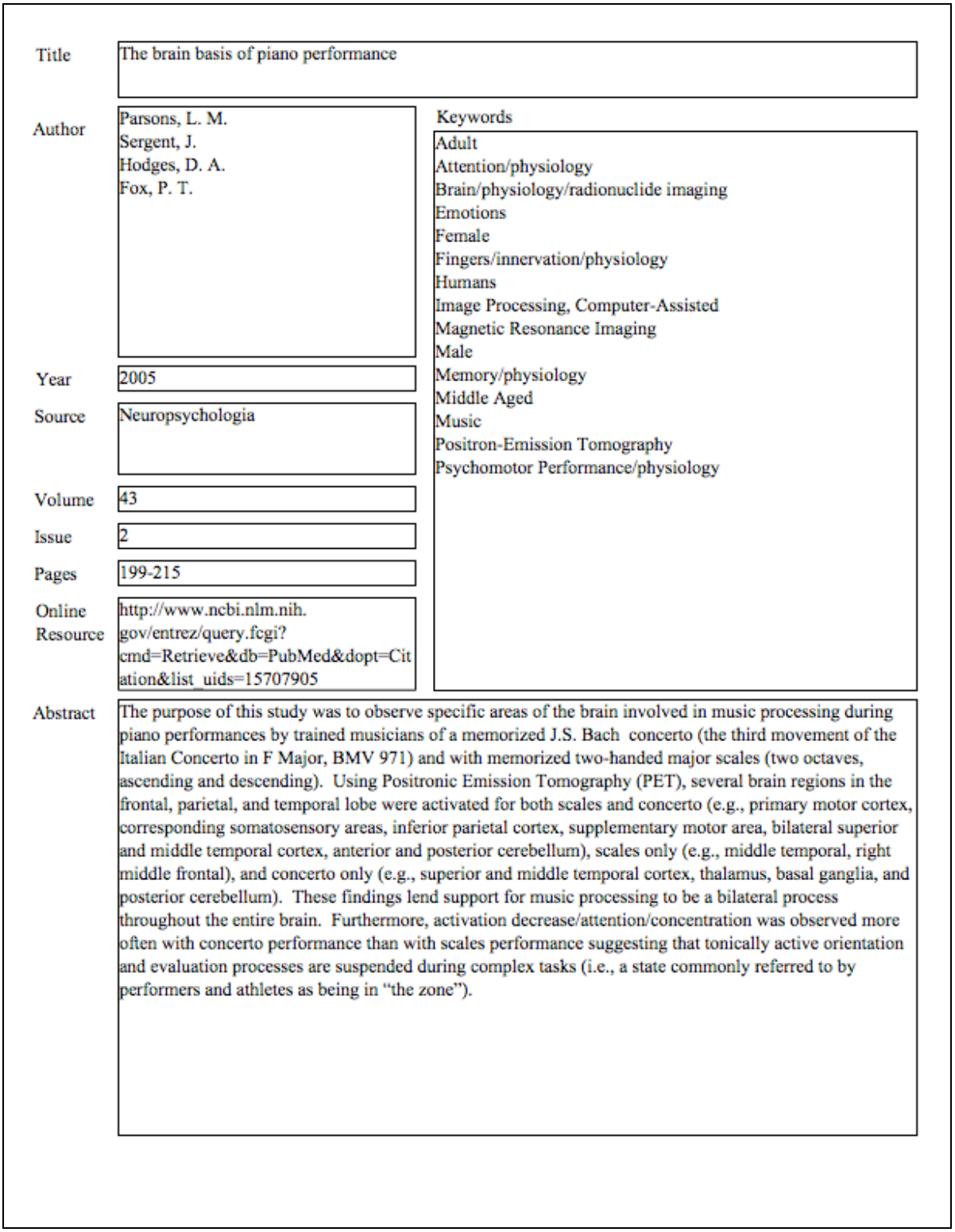
## ***MusicBIRD*** **Presentation Format**

All studies that met any of the qualifying parameters for *MusicBIRD* article selection were evaluated by the researcher. Summative information from each article was entered into the following data fields using electronic storage software (*File Maker Pro© 7.0v3* for Mac OS X, 2004):

- Title
- Author(s)
- Year
- Keywords (original article keywords provided when available)
- Source
- Volume
- Issue
- Online Source (web links provided for *PubMed* articles only)
- Abstract

After reviewing each article, an abstract was written by the dissertation author to serve as a musician's perspective of that particular area of neuromusical research. While some concepts from the scientific literature could be explained adequately with musical terms (e.g., "temporal" processes referring to rhythmic processes), it was also necessary to retain many neuroscientific concepts and areas of brain anatomy to fully explain the

conclusions of a given study. The terminology in the summative abstracts may be technically advanced; however, a reader who has studied the review of neuroscience presented in Chapter II will be sufficiently prepared to understand the terms and concepts addressed in each abstract. Figure 14 offers a sample template of how studies are presented in the online database.



| | |
|---|---|
| Title | The brain basis of piano performance |
| Author | Parsons, L. M.<br>Sergent, J.<br>Hodges, D. A.<br>Fox, P. T. |
| Year | 2005 |
| Source | Neuropsychologia |
| Volume | 43 |
| Issue | 2 |
| Pages | 199-215 |
| Online Resource | http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=15707905 |

Keywords

Adult
Attention/physiology
Brain/physiology/radionuclide imaging
Emotions
Female
Fingers/innervation/physiology
Humans
Image Processing, Computer-Assisted
Magnetic Resonance Imaging
Male
Memory/physiology
Middle Aged
Music
Positron-Emission Tomography
Psychomotor Performance/physiology

Abstract

The purpose of this study was to observe specific areas of the brain involved in music processing during piano performances by trained musicians of a memorized J.S. Bach concerto (the third movement of the Italian Concerto in F Major, BMV 971) and with memorized two-handed major scales (two octaves, ascending and descending). Using Positronic Emission Tomography (PET), several brain regions in the frontal, parietal, and temporal lobe were activated for both scales and concerto (e.g., primary motor cortex, corresponding somatosensory areas, inferior parietal cortex, supplementary motor area, bilateral superior and middle temporal cortex, anterior and posterior cerebellum), scales only (e.g., middle temporal, right middle frontal), and concerto only (e.g., superior and middle temporal cortex, thalamus, basal ganglia, and posterior cerebellum). These findings lend support for music processing to be a bilateral process throughout the entire brain. Furthermore, activation decrease/attention/concentration was observed more often with concerto performance than with scales performance suggesting that tonically active orientation and evaluation processes are suspended during complex tasks (i.e., a state commonly referred to by performers and athletes as being in "the zone").

Figure 14. Presentation format of a sample neuromusical study in the *MusicBIRD*

## Content Analysis

As discussed in the previous chapters, the benefit of a neuromusical research database of brain imaging studies is that it offers insights into the pedagogical, psychological, and philosophical foundations of music education. In addition, the *MusicBIRD* may also serve as a useful tool for identifying trends in neuromusical research or areas in need of further of study. To help identify these trends and areas in need of further study, a content analysis of the final database is presented in Chapter IV to show the number and percentage of studies that address the neuromusical research classifications and subtopics presented in Chapters I and II (e.g., neurophysiology, imaging technology, and educational implications of neuromusical research).

# CHAPTER IV

# RESULTS

All of the studies entered into the *MusicBIRD* are presented as a reference list in Appendix A. Of the four electronic databases queried, *PubMed* articles were reviewed first and provided the greatest number of potential studies as well as qualifying entries into *MusicBIRD.* Many studies in *PubMed* were also included in *PsychINFO*, *ERIC*, or *RILM*. In the case of duplicate studies across more than one database, *PubMed* served as the default article online source.

Table 2.
Potential and qualifying articles for the *MusicBIRD* from the four electronic databases used as sources of data.

| Electronic Database | Potential Articles | Qualifying Articles |
|---|---|---|
| *PubMed* | 1,099 | 411 |
| *PsychINFO* | 416 | 35* |
| *ERIC* | 204 | 1* |
| *RILM* | 393 | 26* |
| TOTAL | 2,112 | 473 |

*Note*. The potential articles shown in column 2 show the number of articles yielded by a keyword search for "music" and "brain" in peer reviewed journals through 2006, whereas the qualifying articles in column 3 show the number of articles entered into *MusicBIRD* after satisfying the qualifying parameters for selection addressed in Chapter III. *No duplicate studies were entered into *MusicBIRD,* thus, the databases reviewed after *PubMed* have more qualifying articles than this table indicates.

## Content Analysis

Throughout the course of reviewing the neuromusical studies, every effort was made to use consistent language while writing the text of the musician's perspective abstract. The neuromusical keywords shown in Tables 4-14 were compiled by the author throughout the *MusicBIRD* article entry process for three main reasons: (1) to form a consistent wording system while writing each abstract, (2) to form a potential starting point for researchers conducting keyword searches within the abstract field, and (3) to form a more detailed subtopic level for the content analysis.

Whenever any of the neuromusical keywords in Tables 4 -14 applied to the content of a neuromusical study, these terms were used in the *MusicBIRD* abstract. Furthermore, every term in the neuromusical keyword tables occurs at least once in the abstract field of the *MusicBIRD*. For example, in Table 4 on *Imaging Technology*, every study using electroencephalography includes the term "electroencephalography" in its abstract as well as a parenthetical abbreviation (EEG). Terms separated by a backslash share similar definitions but may occur independently of each other from abstract to abstract. For example, in Table 5 on *Musical Processes*, not every study using "musical imagery" will also include the term "audiation".

For the purposes of identifying research trends or areas in need of further study, the second and third column of each neuromusical keyword table presents the number and percentage respectively of the studies throughout the *MusicBIRD* that address each term. The listing of these keywords does not imply that these are the only neuromusical terms that occurred throughout the text of all of the studies entered into the *MusicBIRD*.

Rather, each of the terms in the neuromusical keyword tables was selected because it dealt with the original authors' research methods and conclusions based on their findings.

The total number of subtopic articles will not be the same as the number of articles for that given topic. This occurs for various reasons including an overlap of neuromusical subtopics from study to study, multiple subtopics within the same study, or changes in the specificity of the research findings over time. For example, in Table 9 on the *Neurophysiology of Music Processing*, the topic "memory" contains 65 articles while the total number of subtopic articles (i.e., short-term and long-term memory rows combined) is only 23. This circumstance occurs since more of the researcher's conclusions presented in the abstracts refer to memory in a general sense rather than in a specific sense (e.g., short-term, or long-term). Furthermore, although 473 articles are currently in the *MusiBIRD*, 39 of these articles are reviews of other neuromusical imaging studies. Thus, all numbers and percentages will be computed based on 434 samples of original neuromusical research through 2006.

Table 3.
*MusicBIRD* content analysis: *Imaging Technology*

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Diffusion Tensor Imaging (DTI) | 2 | 0.46% |
| 2. Electroencephalography (EEG) | 124 | 28.57% |
| 3. Evoked Potential / Event Related Potential (ERP) | 125 | 28.80% |
| 4. Magnetic Resonance Imaging (MRI) | 47 | 10.83% |
| 5. functional Magnetic Resonance Imaging (fMRI) | 62 | 14.29% |
| 6. Magnetoencephalography (MEG) | 33 | 7.60% |
| 7. Positron Emission Tomography (PET) | 37 | 8.53% |
| 8. Transcranial Doppler Ultrasonography (TC), (TCD) | 2 | 0.46% |
| 9. Transcranial Magnetic Stimulation (TMS) | 11 | 2.53% |
| 10. Voxel Based Morphometry (VBM) | 2 | 0.46% |

*Note*. Keyword topics are alphabetically organized in outline form.
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD*.

Table 4.
*MusicBIRD* content analysis: *Musical Processes*

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Composing, improvising | 2 | 0.46% |
| 2. Global, holistic, music excerpts | 54 | 12.44% |
| 3. Harmony, simultaneous pitch, consonance, dissonance | 26 | 5.99% |
| 4. Imagination, mental imagery, musical imagery, audiation | 25 | 5.76% |
| 5. Listening to music | 211 | 48.62% |
| 6. Performing music, performance, perform | 71 | 16.36% |
| 7. Pitch Perception, local, tone, frequency, fine grain, pitch discrimination, intonation | 183 | 42.17% |
| 8. Rhythm, temporal grouping | 70 | 16.13% |
| 9. Texture, auditory localization, balance and blend | 7 | 1.61% |
| 10. Timbre, spectral pattern, signal shape, tone quality | 35 | 8.06% |
| 11. Visual, music notation, music reading, music literacy | 145 | 33.41% |

*Note.* Keyword topics are alphabetically organized in outline form.
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD.*

Table 5.
*MusicBIRD* content analysis: *Methodology*

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Dichotic Listening | 4 | 0.92% |
| 2. Entrainment | 2 | 0.46% |
| 3. Linear Sounds / pure tones | 15 | 3.46% |
| 4. Longitudinal, Long-term study | 23 | 5.30% |
| 5. Medical Treatment/Music Therapy | 6 | 1.38% |
| 6. Medical Resonance Therapy (MRT-Music) | 1 | 0.23% |
| 7. Subjects | | |
| a. Absolute Pitch (AP) | 23 | 5.30% |
| b. Relative Pitch (RT) | 16 | 3.69% |
| c. Adolescent** | 57 | 13.13% |
| d. Adult** | 280 | 64.52% |
| e. Female** | 254 | 58.53% |
| f. Male** | 264 | 60.83% |
| g. Male/Female** | 295 | 67.97% |
| h. Left-hand | 3 | 0.69% |
| i. Right-hand | 21 | 4.84% |
| j. Right- and left-handed | 24 | 5.53% |
| k. Musically trained, musical training | 201 | 46.31% |
| l. Nonmusically trained, nonmusical training | 154 | 35.48% |
| m. Musically and nonmusically trained, musical and nonmusical training | 153 | 35.25% |

*Note.* Keyword topics are alphabetically organized in outline form. "Subject" subtopics are organized by type.
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD.*
** Adolescent, Adult, Female, Male and Male/Female subjects were identified by searching in the Keywords field.

Table 6.
*MusicBIRD* content analysis: *Theoretical Foundations of Cognitive Neuroscience*

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Connectionism | 1 | 0.23% |
| 2. Developmental shifts, developmental periods, developmental windows, critical periods, optimal periods | 3 | 0.69% |
| 3. Hemisphericity** | 102 | 23.50% |
| 4. Modularity/Music Modules | 12 | 2.76% |
| 5. Trion Theory | 2 | 0.46% |

*Note.* Keyword topics are alphabetically organized in outline form.
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD.*
** Hemisphericity was identified by an Abstract field search for "hemisphere"

Table 7.
*MusicBIRD* content analysis: *Philosophical Implications*

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Aesthetic | 4 | 0.92% |
| 2. Origins of Music | | |
| a. Reward and pleasure responses | 2 | 0.46% |
| b. Communication language, linguistic, semantic, syntax | 84 | 19.35% |
| c. Affective Response, Emotion | 46 | 10.60% |
| 3. Ubiquity (of human music processing)** | 4 | 0.92% |

*Note.* Keyword topics are alphabetically organized in outline form
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD.*
** Words in parenthesis are not used in the Abstract field search.

Table 8.
*MusicBIRD* content analysis: *Neurophysiology of Music Processing*

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Affective Responses, Emotions | 46 | 10.60% |
| 2. Blood Flow | | |
| a. Cerebral Blood Flow, CBF | 22 | 5.07% |
| b. Blood Flow Velocity (BFV) | 2 | 0.46% |
| 3. Brain Activity | | |
| a. Activation increase, activity increase, activation strength, activity strength | 65 | 14.98% |
| b. Activation decrease | 21 | 4.84% |
| c. Greater activation, greater activity | 30 | 6.91% |
| 4. Coherence, Coactivity | 17 | 3.92% |
| 5. EEG Brainwave, Alpha, Beta, Delta, Gamma, Theta | 41 | 9.45% |
| 6. Entrainment | 2 | 0.46% |
| 7. Evoked Potentials/Event Related Potentials (ERP) | | |
| a. Mismatched Negativity (MMN) | 39 | 8.99% |
| b. Gamma Band | 6 | 1.38% |
| c. N1/N2/N4 | 27 | 6.22% |
| d. P2/P3/P6 | 41 | 9.45% |
| 8. Focal Dystonia | 8 | 1.84% |
| 9. Genetic, gene | 47 | 10.83% |
| 10. Hemisphericity, hemisphere, laterality, lateral, ipsilateral, bilateral | 165 | 38.02% |
| a. Right hemisphere | 84 | 19.35% |
| b. Left hemisphere | 82 | 18.89% |
| c. Bilateral | 74 | 17.05% |

(continued on next page)

Table 8.
(continued)

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 11. Memory | 64 | 14.98% |
| a. Short-Term memory, working memory | 18 | 4.38% |
| b. Long-Term memory, declarative, procedural | 4 | 0.92% |
| 12. Neural development, morphology | 12 | 47.93% |
| 13. Myelin/ myelination, white matter, fiber tract organization, pyramidal tract | 6 | 1.38% |
| 14. Neurological Disorders and Brain Damage | | |
| a. Amnesia, memory disturbance | 2 | 0.46% |
| b. Amusia, Aprosody, Aprosodia | 16 | 3.69% |
| c. Alexia | 1 | 0.23% |
| d. Aphasia | 6 | 1.38% |
| e. Apraxia | 3 | 0.69% |
| f. Epileptogenic, musicogenic, epilespsy | 12 | 2.76% |
| g. Excision | 3 | 0.69% |
| h. Infarction | 2 | 0.46% |
| i. Lesion | 18 | 4.15% |
| j. Musical Agraphia | 4 | 0.92% |
| k. Hallucination, hallucinosis | 7 | 1.61% |
| 15. Neuromotor, Motor, bodily kinesthetic, finger tapping, somatosensory | 87 | 20.05% |
| 16. Plasticity | 20 | 4.61% |
| 17. Pleasure and Reward Processes | 2 | 0.46% |

*Note.* Keyword topics are alphabetically organized in outline form.
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD.*

Table 9.
*MusicBIRD* content analysis: *Neuromusical Anatomy (Forebrain)*

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Frontal (lobe)** | 93 | 21.43% |
| a. Operculum, rolandic | 12 | 2.76% |
| b. Orbitofrontal cortex, orbital frontolateral | 6 | 1.38% |
| 2. Parietal (lobe)** | 46 | 10.60% |
| a. Motor Cortex, motor | 78 | 17.97% |
| b. Presupplementary motor area | 2 | 0.46% |
| c. Primary motor cortex, Premotor cortex | 28 | 6.45% |
| d. Sensorimotor, sensorymotor | 19 | 4.38% |
| e. Somatosensory, somatosensori | 13 | 3.00% |
| f. Supramarginal gyrus | 10 | 2.30% |
| 3. Occipital (lobe)** | 14 | 3.23% |
| 4. Temporal (lobe)** | 159 | 36.64% |
| a. Heschl's gyrus | 22 | 5.07% |
| b. Auditory cortex | 74 | 17.05% |
| c. Superior temporal sulcus, gyrus | 41 | 9.45% |

*Note.* Keyword topics are alphabetically organized in outline form with subtopics shaded in gray.
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD.*
** Words in parenthesis are not used in the Abstract field search.
*** The Abstract field search for the term "Temporal" (lobe) omitted the phrases "temporal grouping" and "temporal awareness".

Table 10.
*MusicBIRD* content analysis: *Neuromusical Anatomy (Midbrain)*

| Keywords from the MusicBIRD Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Amygdala | 10 | 2.30% |
| 2. Basal Ganglia | 7 | 1.61% |
| 3. Caudate nucleus | 1 | 0.23% |
| 4. Putamen | 4 | 0.92% |
| 5. Globus pallidus | 1 | 0.23% |
| 6. Insula | 22 | 5.07% |
| 7. Cingulate | 14 | 3.23% |
| 8. Corpus Callosum | 7 | 1.61% |
| 9. Hippocampus | 7 | 1.61% |
| 10. Hypothalamus | 1 | 0.23% |
| 11. Precuneus | 9 | 2.07% |
| 12. Thalamus | 6 | 1.38% |

*Note.* Keyword topics are alphabetically organized in outline form with subtopics shaded in gray.
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD*.

Table 11.
*MusicBIRD* content analysis: *Neuromusical Anatomy (Hindbrain)*

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Cerebellum | 29 | 6.68% |
| 2. Brainstem | 1 | 0.23% |

*Note.* Keyword topics are alphabetically organized in outline form.
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD.*

Table 12
*MusicBIRD* content analysis: *Educational Implications*

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Skill acquisition, learn | 32 | 7.37% |
| 2. Error detection | 4 | 0.92% |
| 3. Teach, pedagogy | 4 | 0.92% |

*Note*. Keyword topics are alphabetically organized in outline form.
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD.*

Table 13.
*MusicBIRD* content analysis: *Neural Correlates of Music Processing*

| Keywords from the *MusicBIRD* Abstract field | Number of articles | Percentage of articles* |
|---|---|---|
| 1. Language, linguistic, communication, semantic, syntax | 84 | 19.35% |
| 2. Mathematics, math | 4 | 0.92% |
| 3. Neural substrates (of music processing)** | 27 | 6.22% |
| 4. Spatial intelligence, spatial reasoning, spatial awareness | 34 | 7.83% |

*Note.* Keyword topics are alphabetically organized in outline form.
*The percentage of articles in this table is based on the number of articles for the given keyword divided by 434 articles of original brain imaging research in the *MusicBIRD.*
** Words in parenthesis are not used in the Abstract field search.

**Online Access and Word Search Protocols**

The entire database is currently stored on a hard drive serving the Music Research Institute of The University of North Carolina at Greensboro, at the web address: http://www.uncg.edu/mus/mri/neuromusical.html. The advantages of *FileMaker Pro*© software are that it will allow for word searches within any of the data entry fields (e.g., author, title, keyword, or abstract) throughout the entire database. Furthermore, it will transfer smoothly into an online format allowing the public to use *MusicBIRD* as a neuromusical resource of peer reviewed studies while maintaining effective Internet security measures.

Anyone may access the *MusicBIRD* by entering "guest" into the username field and leaving the password field blank (administrative access is restricted and is the only way to make changes to the *MusicBIRD* system). The search engine of *File Maker Pro*© allows for basic word searches throughout the database in one field, or across all fields. For example, to obtain all of the studies that include the term "pitch discrimination" in the abstract field, left-click on the search icon (a magnifying glass symbol) in the top of the left side toolbar and then enter the words "pitch discrimination" in the blank abstract field (Figure 15). Left-click on the "Perform Find" tab in the left side toolbar to complete the search and yield all of the "pitch discrimination" studies in the *MusicBIRD*.

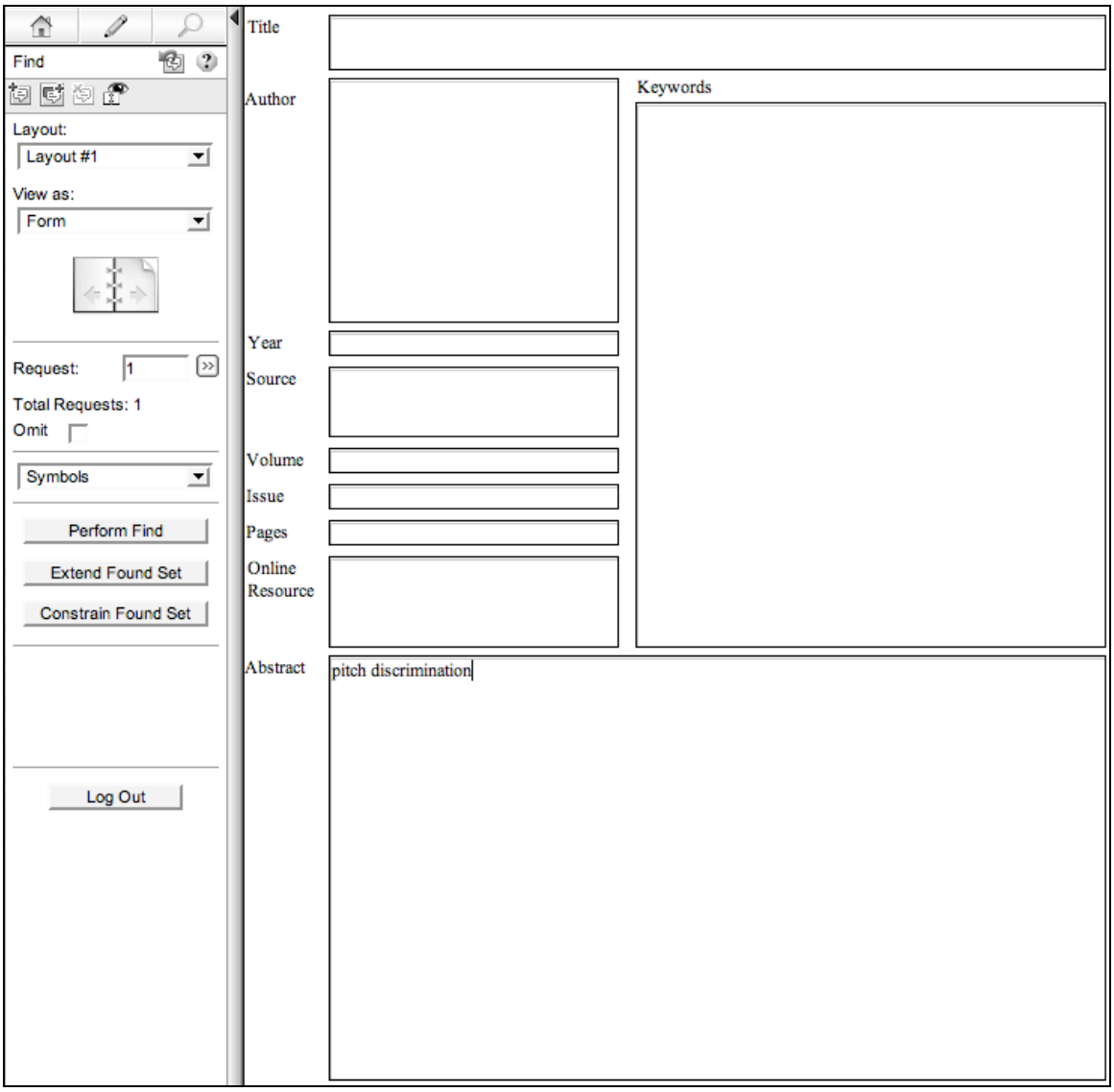



Figure 15. Basic *MusicBIRD* word search procedure

Other search options include an advanced word search using multiple levels of search requests that may omit certain words while yielding other combinations of words across the *MusicBIRD* database. For example, a search for both "rhythm" and "temporal grouping" in the Abstract field could be refined by omitting the word "temporal lobe" to filter out all of the studies that only include the phrase "temporal lobe" while yielding all

the studies that include the words “rhythm” and “temporal grouping”. To conduct an advanced word search that omits certain words yielding other multiple requests for other words and phrases, left-click on the search icon (a magnifying glass symbol) in the top of the left side toolbar to begin a new search and then type the first search word (e.g., “rhythm”) in the abstract field (Figure 16a). Next, left-click on the “add new request” icon in the left side toolbar located below the word “Find” to further refine the search for the word “rhythm” by typing another search word or phrase (e.g., “temporal grouping”) in the Abstract field (Figure 16b). Notice in the left hand column of Figure 16b that the second level of an advanced search will be labeled as “Request 2” in the Request field. More words and phrases can be added and each successive “add new request” will increase the number in the Request field. Finally, left-click “add new request” once more and select “omit” in the left hand column checkbox followed by typing the word or phrase that needs to be omitted from the overall search in the abstract (e.g., “temporal lobe” in Figure 16c). When all desired and omitted words have been entered, left-click the “Perform Find” tab to yield the resulting studies (Figure 16d). Scrolling through the yielded studies is accomplished by left-clicking the “right” and “left” arrows above the Record number index.

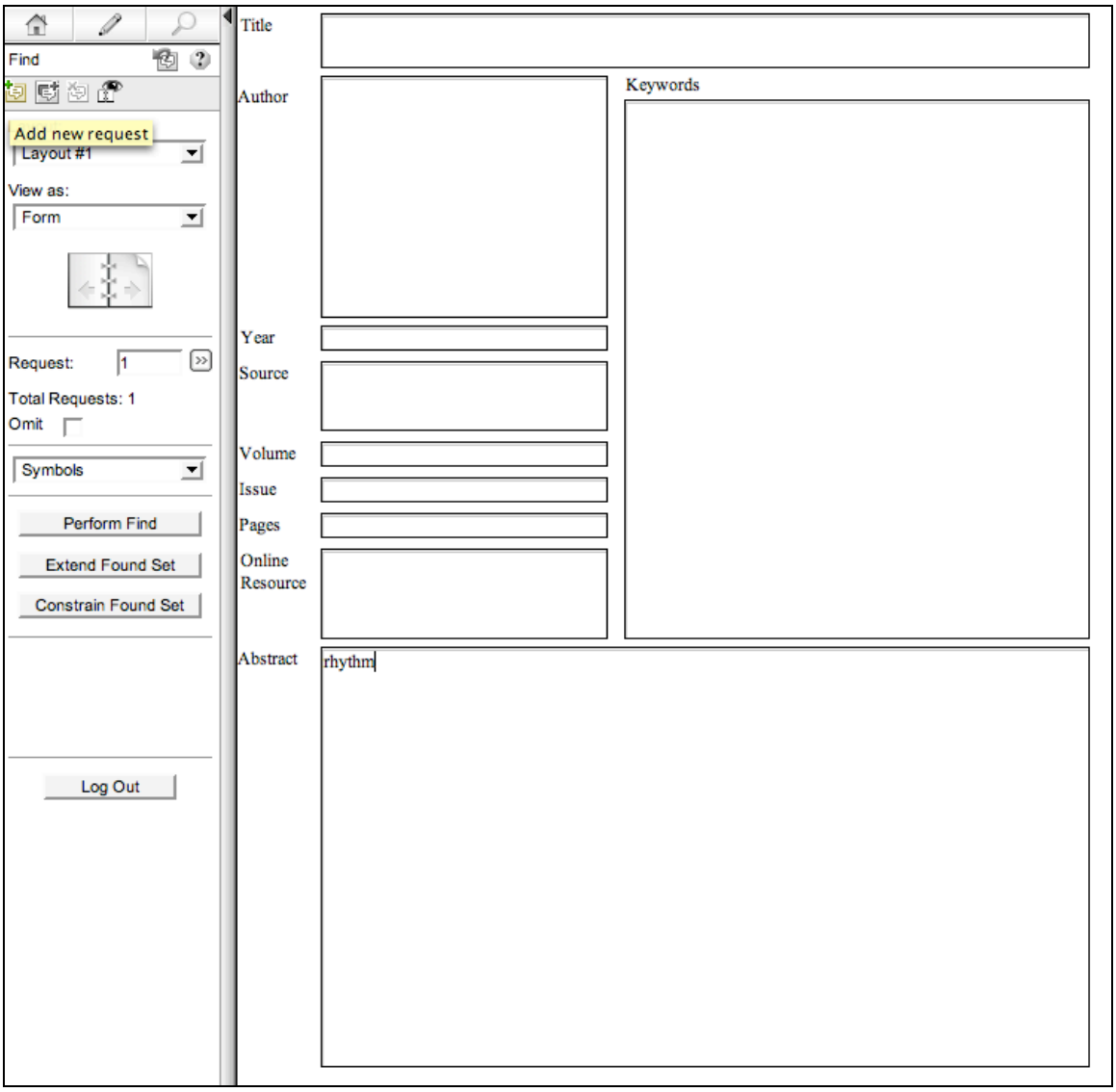



Figure 16a. Advanced *MusicBIRD* word search: Request 1

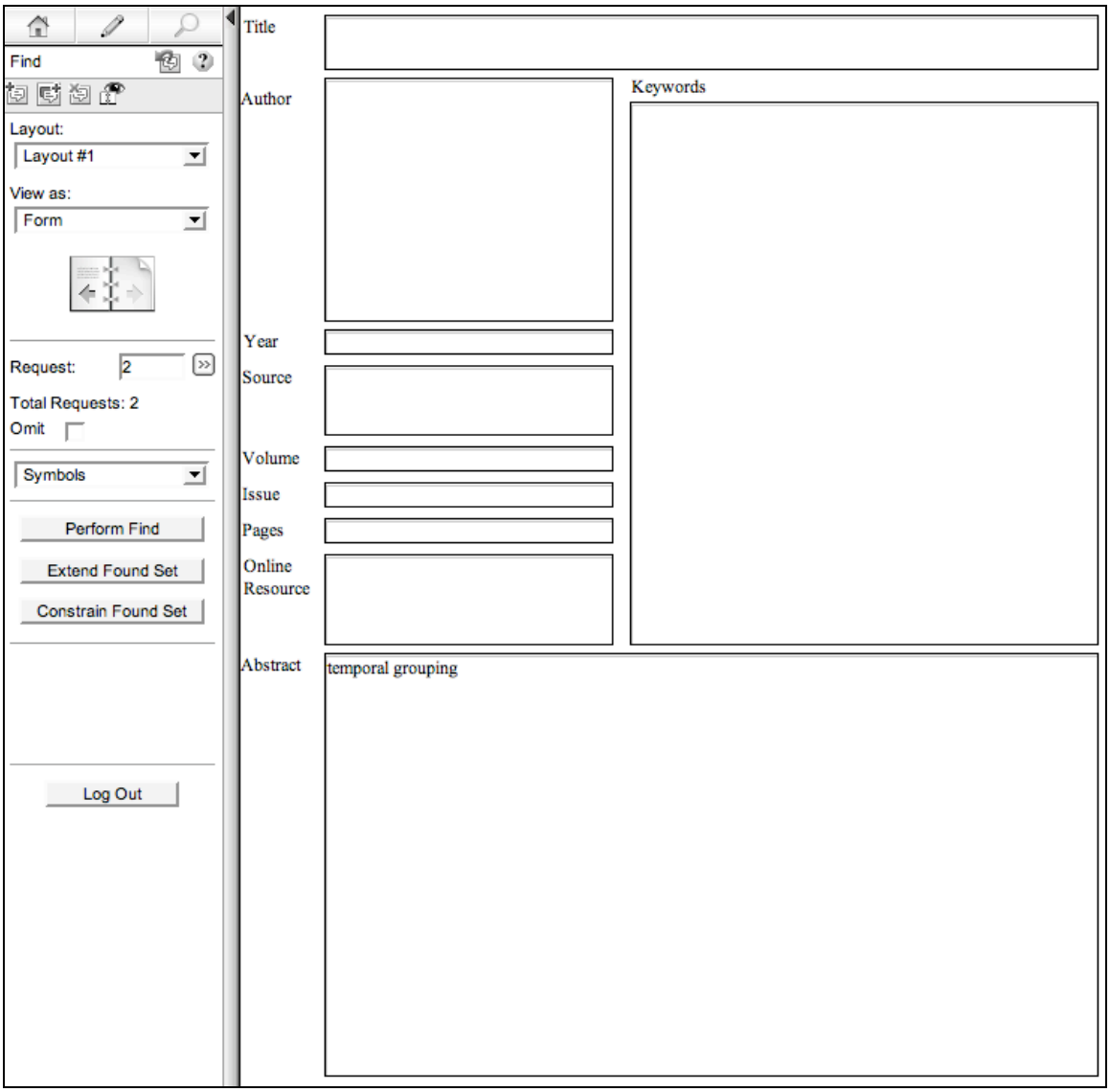



Figure 16b. Advanced *MusicBIRD* word search: Request 2

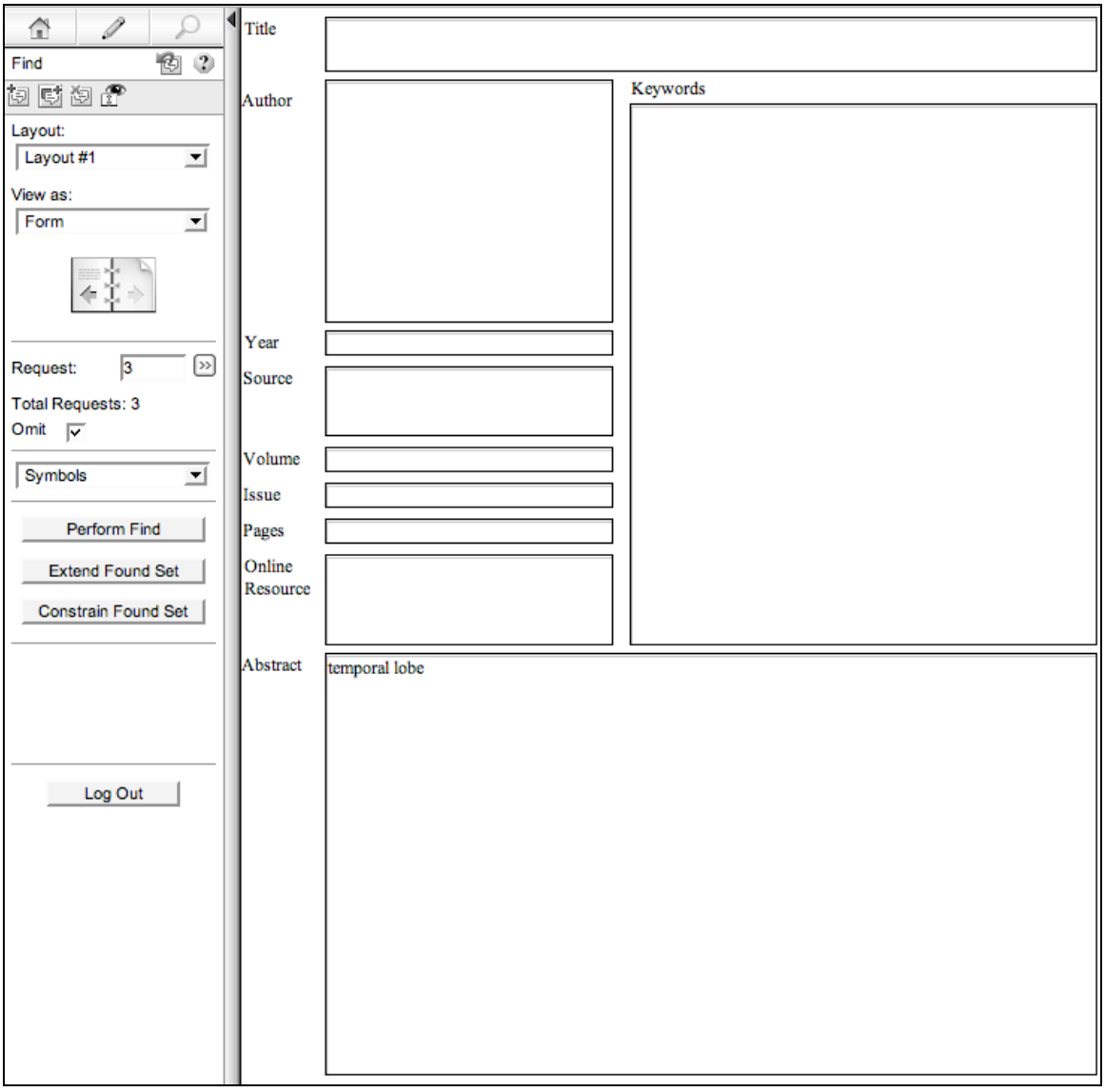



Figure 16c. Advanced *MusicBIRD* word search: Request 3

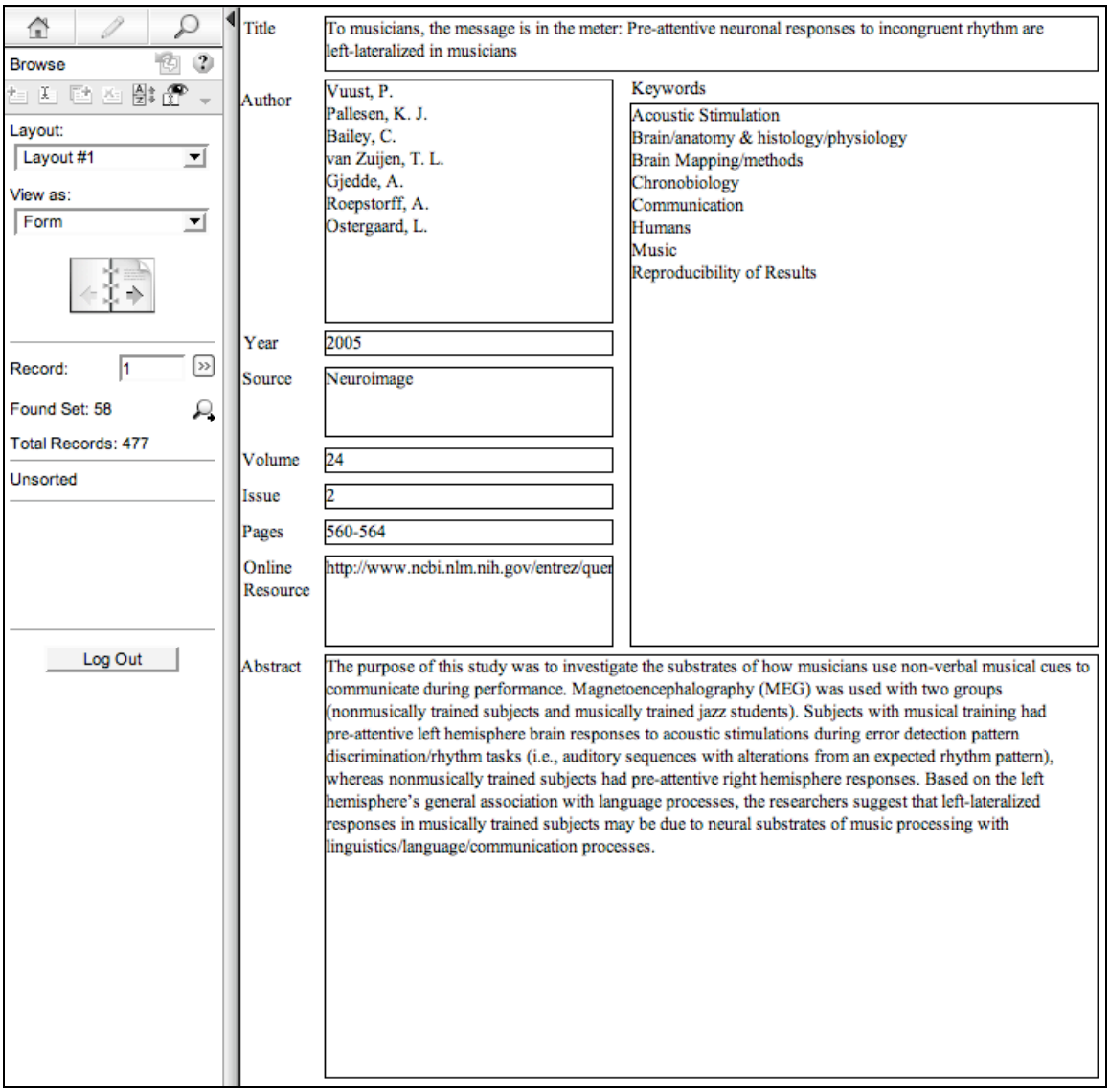



Figure 16d. Advanced *MusicBIRD* word search results

# CHAPTER V

# SUMMARY AND CONCLUSIONS

## Introduction

There is a growing interest for neuromusical research in both the neuroscience and the music education professional community. Given the rising number of neuromusical studies in the past decade, in conjunction with multiple databases of neuromusical research offering varied sources of imaging studies relating to music and the brain, the primary objective of this dissertation was to assess and clarify the current state of neuromusical research by creating a Musical Brain Imaging Research Database (*MusicBIRD*) to present summary information from all peer-reviewed studies of brain imaging neuromusical research as identified by prominent research databases (e.g., PubMed and RILM).

In addition to original peer-reviewed neuromusical research, the *MusicBIRD* also contains conference proceedings and other sources of neuromusical research selected at the author's discretion such as articles written to summarize and review important developments in neuromusical research. All studies included in the *MuiscBIRD* display commonly cited reference information (e.g., title, author, source) including the original study authors' keywords and an abstract written in a musician's perspective by the dissertation author to report the study purpose, procedures, subject criteria, results and conclusions.

The secondary objectives of this dissertation were:

1. To identify any trends across the field of neuromusical research (e.g., methodology, subject criteria, and research topics),

2. To reveal any implications from neuromusical research serving the pedagogical, psychological, and philosophical foundations of music education, and

3. To recommend future areas of neuromusical research.

## Summary

All studies that potentially qualified for inclusion in the *MusicBIRD* were identified by a keyword search for "music" and "brain" in the following electronic research databases: PubMed, PsychINFO, ERIC, and RILM. Across all databases through 2006, this keyword search yielded 2,112 potential articles of which 442 dealt with original investigations of music processes using brain imaging and were thus selected and entered into the current *MusicBIRD*. Also, 39 articles written as a review to address important discoveries in neuromusical research were included, however, all of the trends and percentages reported in the following pages were factored using only the 442 original neuromusical studies. The decision to include these review-based articles was to highlight the importance of experienced researchers' comprehensive views of multiple neuromusical studies and the insights gained from other studies not necessarily their own.

For example, Isabelle Peretz and Robert Zatorre have been investigating the musical brain for nearly thirty years. In a recent article summarizing what has been learned about musical brain processes they wrote, "Musicians appear to recruit more neural tissue or to use it more efficiently than do nonmusicians" (2005, p. 105). Based on

a review of the extant neuromusical research, their statement deserves only a small critique being that except for cases of extremely rare neurological disorders such as amusia (i.e., the inability to process music in the brain), all people possess the ability to be musicians if they are given the opportunities and experiences to develop their natural musical capacity. A more appropriate paraphrase of Peretz's and Zatorre's quote, (as well as a summarizing statement for this entire dissertation) would be that when it comes to engaging in musical tasks, "musically trained people appear to recruit more neural tissue or to use it more efficiently than do nonmusically trained people."

## Trends in Neuromusical Research

### *Methodology*

The three most commonly used brain imaging devices identified in the *MusicBIRD* were Electroencephalography (EEG) with 28.80%, Event Related Potentials (ERP) with 15.67%, and functional Magnetic Resonance Imaging (fMRI) with 15.21%. The most common forms of music processing conditions were listening to excerpts of recorded music (52.07%) or engaging in pitch perception tasks (37.33%). The latter condition refers to experiences lacking a greater musical context such as discriminating isolated tone sequences for pitch frequency or timbre.

### *Subject Characteristics*

While many researchers did not identify the musical history of the subjects in their studies (51.35%), the musical experiences of the subjects was an important factor in many other studies with some specifically designed for musically trained subjects (14.25%), nonmusically trained subjects (8.82%), or both musically and nonmusically

trained subjects (25.57%). Furthermore, while the studies that identified the gender of the subjects were nearly balanced (male subjects were used 60.18% of the time, female subjects were used 58.14%), the most common age for subjects was in the adult range (64.03%) compared to adolescents (12.90%). Although the age of the subjects was not identified 23.07% of the time, this discrepancy of subject age may be even greater since researchers using adolescent subjects usually make a point of identifying the fact that their subjects are adolescents due to the implications of brain processes that are still in a developmental phase.

*Musical Processes*

Many different aspects about the neurophysiology of music processing have been examined and identified. The most widely reported musical neurophysiological processes include changes in brain activity such as EEG patterns or Cerebral Blood Flow (35.57%), hemisphericity, or the lateralization of brain activity (35.29%), neuromotor functions (19.23%), neurological disorders (15.61%), the role of memory (14.71%), affective responses or emotional systems (11.99%), and mismatch negativity (MMN) (10.41%) which is the brain's ERP response to a deviant stimulus when an expected stimulus was thought to occur (e.g., if a listener was expecting to hear a Perfect Authentic Cadence and instead heard a Deceptive Cadence, this would likely elicit a MMN response in the listener's brain).

The neurophysiological differences between musically and nonmusically trained brains are most prominent in terms of neural efficiency and plasticity. Musically trained subjects demonstrate greater accuracy and faster response times in musical discrimination

tasks (e.g., pitch matching, or temporal grouping) than nonmusically trained subjects. Furthermore, when engaging in musical tasks, many studies have identified that musically trained people tend to activate larger and/or stronger neural networks than nonmusically trained subjects in many areas throughout the brain such as the auditory cortex (17.19%), the motor cortex (8.82%), the cerebellum (6.56%), and Heschl's Gyrus (5.42%).

As noted earlier in Chapter I, one of the most heavily debated topics of neuromusical research deals with the possibility for neural network correlates of musical processes, or put more simply, whether nonmusical brain processes like math or language are related or affected in any way by musical brain processes. This question will continue to be unfulfillingly answered until multiple longitudinal studies are completed that compare the brain development and behavioral performance in various tasks (e.g., mathematical, linguistic, spatial, etc.) of musically and nonmusically trained subjects that have been observed from early childhood through adulthood. In the meantime, however, there have been several short-term brain imaging studies examining the possible connections between musical and nonmusical processes such as language and linguistics (16.74%), spatial reasoning (7.69%), or math skills (0.90%).

## Implications

The challenge of addressing the implications of the *MusicBIRD* studies is that drawing connections between neuromusical research and pedagogy, psychology, and philosophy is still a work in progress. To the curious researcher, every study contained in the *MusicBIRD* presents an interesting idea about the process of human musicality that is

worthy of further investigation, but the challenge to music educators and neuroscientists will be addressing all of the interesting ideas that are uncovered in each study without falling into the whimsical perspective that neuroscience is the answer to all educational issues. What is needed in the next stage of neuromusical research is a balance between enthusiastic speculation and conservative discretion. This chapter attempts to set the tone of that balance.

Perhaps the greatest implication of this dissertation is that with the collection of many different types and sources of original neuromusical research into one concise database, there will now be a more comprehensive presentation of this research than ever before. In terms of the general implications of neuromusical research for the music education profession as a whole there are many ways to address such a broad topic; however, based the experience of selecting and reviewing a nearly complete historical catalog of brain imaging neuromusical studies, the field of neuroscience contains several noteworthy implications related to the advocacy, pedagogy, and philosophy of music education.

First of all, the ubiquity of human music processing is one of the strongest arguments for the advocacy of music education programs. In addition to extensive evidence presented by anthropologists, archaeologists, and sociologists identifying the consistent use of music in every civilization throughout human history (Dubos, 1981; Lomax, 1968; Merriam, 1964), neuromusical studies have also helped demonstrate that the capacity for music is available to anyone who has the opportunity to develop this capacity (Norton et al., 2005; Peretz, 2006). The growing evidence for humanity's

common use of music weakens the idea that musical skill is a unique genetic gift and not a basic human trait. Even the argument for tone loses its strength when one removes the factor of musical training.

For example, a recent paper by Diana Deutsch reported that 74% of musically trained people who were raised from birth to speak tonal languages (i.e., languages like Chinese that have identically sounding words with different meanings in which the pitch of a word is its only distinguishing characteristic) were found to have absolute pitch (AP), whereas only 14% of musically trained people from non-tonal languages (in this case, English) possessed AP (Deutsch, Henthorn, & Dolson, 2004). Although there may be genetic traits that promote or discourage musical processes, it appears that the quality and quantity of one's musical experiences are the most crucial factors for the development of human musicality.

Neuromusical research will likely strengthen some traditional pedagogical practices in music education while challenging other philosophical stances in our profession. For example, the value of establishing good habits during initial music training experiences (e.g., the first lesson on an instrument) are reinforced by brain imaging data showing that the neural network patterns that are created during the first moment of a student's first piano lesson stay with that student throughout all future piano experiences (Bangert & Altenmüller, 2003). Another pedagogical reinforcement relates to how musical imagery (e.g., having students imagine their musical task rather than actually performing it) has been shown to activate similar areas of the auditory cortex as compared to actual performance with sound (Halpern & Zatorre, 1999; Penhune et al.,

1998; Yoo et al., 2001; Zatorre et al., 1996). This suggests that helping students to imagine only a melodic line may effectively help them refine the melody by filtering out the other complicating factors of a passage, such as tricky intonation or even performance anxiety.

Currently, modularity is the most widely accepted and supported theory of how the brain engages in musical processes. Modularity refers to how various aspects of music processing (e.g., pitch or timbre discrimination, rhythmic timing, emotional responses, motor functions, memories) are specifically localized to distinct regions of the brain, yet the whole of music processing engages widely distributed areas throughout the brain. Whether subjects have engaged in music listening or performance tasks, modularity has been reinforced through numerous hemispheric brain activation differences revealed in EEG studies (Overman, Hoge, Dale, Cross, & Chien, 2003; Peretz, 2006) as well as the fine degree of neural activity detail that has been identified in numerous neuromusical MRI studies.

For most practicing music educators, simply knowing that the right auditory cortex is more active during pitch matching tasks or that the left auditory cortex is more active during rhythmic accuracy tasks may not be as valuable to a music teacher as figuring out which pedagogical approach will help a student learn to make music with good intonation and a steady beat. However, many successful music teachers have identified the importance of isolating each concept that a student needs to improve upon rather than trying to have students focus on several different performance traits at the same time. In the tradition of Heinrich Pestalozzi and John Dewey, good teaching stems

from leading students from the whole idea to its parts, and back again. Further investigation is warranted to study whether awareness of how the human brain has a distinct neural network specifically dedicated to each of the fundamental performance traits that students are trying to develop. Research in this area could possibly help some music teachers address the need to break down the complexity of a student's musical performance task to its isolated parts before trying to put it all back together again into a holistic musical experience.

One example of how neuroscience can be beneficial to educators is the case of researchers who identified hundreds of middle-school students with both the poorest math scores as well as the poorest self-perception of their personal intelligence (Blackwell, Trzesniewski, & Dweck, 2007). In short, these students did not do well in math and appeared to possess a fixed mindset that they were not smart enough to ever improve in math no matter what kind of help they got. The researchers divided the low self-perception students into two groups: one received standard math tutoring sessions throughout the year, and the other group received a neuroscience primer on how the brain functions and learns new skills as new neural connections are made for each new experience. The tutoring session students did not show any improvement in their math scores for that year, however, the neuroscience primer group significantly improved their math scores. As this story illustrates, neuroscience and education are tied together and the implications of how these two fields might serve one another is only beginning to be explored.

## Limitations

The scope of this study is widespread and the possibility for omitting some research from the final database was a risk, however, by searching electronic databases containing peer-reviewed neuromusical research such as PubMed and RILM, there is great confidence that a vast majority of musical brain imaging studies were identified and reviewed. Still, there are considerations worth reporting that may limit the comprehensiveness of the *MusicBIRD* to represent all neuromusical brain imaging research. These considerations are:

1. The possibility that some neuromusical research was not yielded by a keyword search for "music" and "brain",
2. That electronic databases other than PubMed, PsychINFO, ERIC, and RILM might contain additional peer-reviewed neuromusical research,
3. Some non-English neuromusical studies may not have been yielded by the search parameters, and
4. Some studies with promising titles such as "Dynamic aspects of the human electroencephalogram: 1st results of a radio-telemetric study" (Arfel, Casanova, & Coulmance, 1969) did not yield an online abstract, links to electronic text, or have any availability through the author's library resources.

As a musician, the author recognizes the challenge of engaging the field of neuroscience without a neuroscience background. To address this concern, several steps were taken to ensure the highest standards of research throughout the dissertation process. The dissertation committee has included the critical advice and input of professional leaders with extensive experience in music education, performance, psychology, and neuroscience. Carefully reviewing the research process with the dissertation committee and accredited neuroscientists has helped guard against any

misinterpretations or damaging omissions by the author. Furthermore, the author has sought a greater understanding of neuroscience by taking a neurobiology course as part of his doctoral plan of study, reading numerous journals, texts, and articles related to the study of the brain, and even participating as a musically trained subject in a neuromusical brain imaging study.

## Recommendations For Future Neuromusical Research

### *Pedagogy*

Many studies have investigated the physiology of music processing, or compared the difference in brain activity between groups of musically and nonmusically trained subjects, however, relatively few studies have used brain imaging to investigate the effect of various pedagogical approaches (e.g., teacher modeling compared to teacher verbal instruction) on the brain activity of students in music learning conditions to observe if and which type of pedagogy has an effect on students' brain patterns. For example, behavioral observations in conjunction with ERP readings of student brain activity during contrasting pedagogical music learning conditions could be a valuable method to identify the brain patterns of music students that represent heightened modes of concentration, and whether pedagogical techniques correspond to heightened levels of concentration and improved performance.

### *Longitudinal Studies*

From an advocacy standpoint, the role of music education in schools is strengthened by evidence from anthropology and neuroscience that music processes are a

ubiquitous human trait. The potential for controversy is enhanced though when neuromusical research is used to defend the idea that musical abilities improve other forms of human intelligence such as mathematics, language skills, or spatial reasoning. While a majority of educators have distanced themselves from endorsing the value of music education strictly for nonmusical purposes, it was not so long ago that the media attention on the "brain power" of music lead governor Zel Miller to present each Georgia newborn with a classical CD recording, or that the Mozart Effect was touted by the leading conference in our profession as one of the values of getting a music education (Price, 1999). While neuromusical studies may continue to excite some people to extrapolate greater consequences of music's correlates for nonmusical abilities than are justifiably reasonable, the only acceptable means to evaluate the potential of whether musical training affects nonmusical skills will be through repeated, longitudinal, peer-reviewed studies. At this time, evidence to support either side of this argument is unavailable due to the limited number of longitudinal studies that have been completed.

*Further Recommendations*

In addition to the pedagogical and longitudinal research areas recommended above, there are several other areas worthy of investigation using brain imaging methodology that would serve both the neuroscience and music education community. Based on my review of neuromusical related literature, the complete list of these recommendations include brain imaging studies in the following research areas:

1. Music teaching pedagogies and the brain activity associated with music learning

2. Longitudinal studies of brain morphology and music training neural development

3. The neural conditions associated with readiness for musical training (e.g., the potential for an association between myelination developmental windows), especially with increases in the number of studies involving adolescents

4. Cross-cultural studies of musically trained subjects to compare the brain morphology associated with growing up exposed to one or more musical cultures (e.g., a comparison of Asian and Western musical traditions)

5. Comparisons of musical processes between young and old, or male and female subjects,

6. Composition, improvisation and prepared performance on all instrument and vocal types,

7. The effect of music processing on neurotransmitter levels

8. The potential for shared, proximal, or distinct neural networks dedicated to music and non-music systems (e.g., language processes)

9. Emotional responses to music processing, especially during music performance tasks

## Conclusion

Both neuroscientists and teachers are interested in studying how the brain works: the former to understand and improve the function of an organ that is responsible for how a human thinks, the latter to understand and improve the function of an organ that is responsible for how a student learns. Not only have neuromusical researchers offered insights to music teachers about how fascinating the study of the brain can be, but they have also shown that when applied in an appropriate context, neuroscience can be a powerful educational tool. While the extent of that context is still limited, further investigation of how the brain works may offer a new perspective on how best to teach,

learn, and perform music. As neuromusical research continues to accumulate at an expanding rate, the *MusicBIRD* may serve as a valuable resource for researchers, teachers, and students by providing a systematic and comprehensive overview of the studies associated with the musical brain.

# REFERENCES


Abbott, A. (2002). Music, maestro, please! *Nature, 416*(6876), 12-14.

Alkon, D. (1989). Memory storage and neural systems. *Scientific American, 261*(1), 42-50.

Altenmüller, E. O. (2001). How many music centers are in the brain? *Annals of the New York Academy of Science, 930*, 273-280.

Arfel, G., Casanova, C., & Coulmance, M. (1969). [Dynamic aspects of the human electroencephalogram. 1st results of a radio-telemetric study]. *Electroencephalography and Clinical Neurophysiology, 27*(3), 225-237.

Arnadottis, G. (1990). *The brain and behavior*. St. Louis: C. B. Mosby.

Baharloo, S., Service, S., & Risch, N. (2000). Familial aggregation of absolute pitch. *The American Journal of Human Genetics, 67*, 755-758.

Bangert, M., & Altenmüller, E. O. (2003). Mapping perception to action in piano practice: a longitudinal DC-EEG study. *BMC Neuroscience, 4*(26), 14.

Barrett, D. L. (1993). Relationship of musical audiation to musical training, musical proficiency and scholastic achievement among advantaged and disadvantaged 6-to-8 year olds. (Doctoral dissertation, Columbia University Teachers College). *Dissertation Abstracts International, 54*(12), 4383A.

Bartlett, D. (1996). Physiological responses to music and sound stimuli. In D. Hodges (Ed.), *Handbook of music psychology* (2nd ed.). University of San Antonio: IMR Press.

Bartlett, D., Kaufman, D., & Smeltekop, R. (1993). The effects of music listening and perceived sensory experiences on the immune system as measured by interleukin-1 and cortisol. *Journal of Music Therapy, 30*(4), 194-209.

Bengtsson, S. L., & Ullen, F. (2006). Dissociation between melodic and rhythmic processing during piano performance from musical scores. *Neuroimage, 30*(1), 272-284.

Berns, G. (2005). *Satisfaction: The science of finding true fulfillment*. New York: Henry Holt.

Besson, M., & Faïta, F. (1995). An event-related potential (ERP) study of musical expectancy: comparison of musicians with nonmusicians. *Journal of Experimental Pscyhology: Human Perception, 21*, 1278-1296.

Besson, M., Faita, F., & Requin, J. (1994). Brain waves associated with musical incongruities differ for musicians and non-musicians. *Neuroscience Letters, 168*(1-2), 101-105.

Blacking, J. (1973). *How musical is man?* Seattle: University of Washington Press.

Blackwell, L., Trzesniewski, K., & Dweck, C. S. (2007). Implicit Theories of Intelligence Predict Achievement across an Adolescent Transition: A Longitudinal Study and an Intervention. *Child Development, 78*(1), 246-263.

Blood, A., & Zatorre, R. J. (2001). Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *Proceedings of the National Academy of Sciences of the United States of America, 98*(II), 818-823.

Bloom, F., Lazerson, A., & Hofstadter, l. (1985). *Brain, mind, and behavior*. New York: Freeman.

Blumstein, S., Goodglass, H., & Tartter, V. (1975). The reliability of ear advantage in dichotic listening. *Brain and Language, 2*, 226-236.

Booth, J. N., Koren, S. A., & Persinger, M. A. (2005). Increased feelings of the sensed presence and increased geomagnetic activity at the time of the experience during exposures to transcerebral weak complex magnetic fields. *International Journal of Neuroscience, 115*(7), 1053-1079.

Bryden, M. (1963). Ear preferences in auditory perception. *Journal of Experimental Psychology, 65*, 103-105.

Bunzeck, N., Wuestenberg, T., Lutz, K., Heinze, H. J., & Jäncke, L. (2005). Scanning silence: mental imagery of complex sounds. *Neuroimage, 26*(4), 1119-1127.

Butzlaff, R. (2000). Can music be used to teach reading? *Journal of Aesthetic Education, 34*(3-4), 167-178.

Byo, J. L. (1990). Recognition of intensity contrasts in gestures of beginning conductors. *Journal of Research in Music Education, 38*, 157-163.

Carey, B. (2005, October 18, 2005). Can brain scans see depression? *The New York Times*.

Carter, R., & Frith, C. (1998). *Mapping the mind*. Los Angeles: University of California Press.

Chan, A. S., Ho, Y.-C., & Cheung, M. C. (1998). Music training improves verbal memory. *Nature, 396*, 128-129.

Chomsky, N. (1986). *Knowledge of language: Its nature, origin, and use*. New York: Praeger.

Churchland, P. (1993). *Matter and consciousness* (Rev. ed.). Cambridge: MIT Press.

Churchland, P. (2003). *Self-representation in nervous systems* (Vol. 1001). New York: The New York Academy of Sciences.

Ciepluch, G. M. (1988). Sightreading achievement in instrumental music performance, learning gifts, and academic achievement: a correlation study. (Doctoral dissertation, The University of Wisconsin - Madison). *Dissertation Abstracts International, 49*(06), 1398A.

Cui, H. W., Zhang, S. Z., Di, H. B., Liu, H., Zhu, Y. H., Zhang, Q. W., et al. (2005). [Functional MRI of human brain in musicians and non-musicians]. *Zhejiang Da Xue Xue Bao Yi Xue Ban, 34*(4), 326-330.

Curtiss, S. (1977). *Genie: A psycholinguistic study of a modern-day "wild child"*. New York: Academic Press.

Darwin, C. (1871). *The origin of species*. New York: Modern Library.

DaSilva, A. F., Tuch, D. S., Wiegell, M. R., & Hadjikhani, N. (2003). A primer on diffusion tensor imaging of anatomical substructures. *Neurosurgical Focus, 15*(1), E4.

Demorest, S. (2000). Does music make you smarter? *Music Educator's Journal, 87*(2), 33-39, 58.

Deutsch, D. (1999). *The psychology of music* (2nd ed.). New York: Academic Press.

Deutsch, D., Henthorn, T., & Dolson, M. (2004). Absolute pitch, speech, and tone language: Some experiments and a proposed framework. *Music Perception, 21*(3), 339.

Di Pietro, M., Laganaro, M., Leemann, B., & Schnider, A. (2004). Receptive amusia: temporal auditory processing deficit in a professional musician following a left temporo-parietal lesion. *Neuropsychologia, 42*(7), 868-877.

Dowling, W. J. (1988). Tonal structure and children's early learning of music. In J. Sloboda (Ed.), *Generative processes in music* (pp. 113-128). Oxford: Clarendon Press.

Drayna, D., Manichaikul, A., de Lange, M., Snieder, H., & Spector, T. (2001). Genetic correlates of musical pitch recognition in humans. *Science, 291*, 1969-1971.

Drennan, C. B. (1984). The relationship of musical aptitude, academic achievement and intelligence in merit (gifted) students of Murfreesboro City Schools (Tennessee). (Doctoral dissertation, Tennessee State University). *Dissertation Abstracts International, 46*(12), 3581A.

Drubach, D. (2000). *The brain explained*. Upper Saddle River, NJ: Prentice Hall Health.

Dubos, R. (1981). *Celebrations of life*. New York: McGraw-Hill.

Duke, R. A., Flowers, P. J., & Wolfe, D. E. (1997). Children who study piano with excellent teachers in the United States. *Bulletin of the Council for Research in Music Education, 132*, 51-84.

Edmister, W. B., Talavage, T. M., Ledden, P. J., & Weisskoff, R. M. (1999). Improved auditory cortex imaging using clustered volume acquisitions. *Human Brain Mapping, 7*(2), 89-97.

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., & Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science, 270*(5234), 305-307.

Epstein, H. (1978). Growth spurts during brain development: Implications for educational policy and practice. In J. Chall & A. Mirsky (Eds.), *Education and the brain*. Chicago: University of Chicago Press.

Epstein, H. (1986). Stages in human brain development. *Developmental Brain Research, 30*, 114-119.

Evers, S., & Suhr, B. (2000). Changes of the neurotransmitter serotonin but not of hormones during short time music perception. *European Archives of Psychiatry and Clinical Neuroscience, 250*(3), 144-147.

Flohr, J., & Hodges, D. A. (2002). Music and neuroscience. In R. Colwell & C. Richardson (Eds.), *The New Handbook of Research on Music Teaching and Learning* (pp. 991-1008). New York: Oxford University Press.

Flohr, J., Persellin, D., & Miller, D. (1996). *Children's electrophysical responses to music.* Paper presented at the 22nd International Society for Music Education World Conference, Amsterdam, The Netherlands.

Fox, D. (2000). Music and the baby's brain: Early experiences. *Music Educator's Journal, 87*(2), 23-27, 50.

Fox, P., Sergent, J., Hodges, D. A., Martin, C., Jerabek, P., Glass, T., et al. (1995). *Piano performance from memory: A PET study.* Paper presented at the Human Brain Mapping Conference, Paris.

Fries, W., & Swihart, A. A. (1990). Disturbance of rhythm sense following right hemisphere damage. *Neuropsychologia, 28*(12), 1317-1323.

Frisina, R. D. (2001). Subcortical neural coding mechanisms for auditory temporal processing. *Hearing Research, 158*(1-2), 1-27.

Fujioka, T., Trainor, L. J., Ross, B., Kakigi, R., & Pantev, C. (2004). Musical training enhances automatic encoding of melodic contour and interval structure. *Journal of Cognitive Neuroscience, 16*(6), 1010-1021.

Gaab, N., Gaser, C., Zaehle, T., Janäcke, L., & Schlaug, G. (2003). Functional anatomy of pitch memory: an fMRI study with sparse temporal sampling. *Neuroimage, 19*, 1417-1426.

Gardner, H. (1983). *Frames of mind: The theory of multiple intelligences*. New York: BasicBooks.

Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. *Journal of Neuroscience, 23*(27), 9240-9245.

Gaston, E. T. (1968). Factors contributing to responses in music. In E. T. Gaston (Ed.), *Music Therapy*. Lawerence, KS: Allen Press.

Gazzaniga, M. (2005). *The ethical brain*. New York: Dana Press.

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., et al. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences of the United States of America, 101*(21), 8174-8179.

Graziano, A. B., Peterson, M., & Shaw, G. (1999). Enhanced learning of proportional math through music training and spatial-temporal training. *Neurological Research, 21*, 139-152.

Greenough, W. T. (1984). Possible structural substrates of plastic neural phenomena. In G. Lynch, J. L. McGaugh & N. M. Weinberger (Eds.), *Neurobiology of Learning and Memory* (pp. 470-478). New York: Guilford Press.

Gregersen, P., Kowalsky, E., Kohn, N., & Marvin, E. (2000). Early childhood music education and predisposition to absolute pitch: teasing apart genes and environment. *The American Journal of Human Genetics, 98*, 280-282.

Gruhn, F., & Rauscher, F. H. (Eds.). (2007). *Neurosciences in music pedagogy*: Nova Science Publishers.

Gulick, W., Gescheider, G., & Frisina, R. (1989). *Hearing: Physiological acoustics, neural coding, and psychoacoustics*. New York: Oxford University Press.

Haack, P. A. (1972). Use of positive and negative examples in teaching the concept of musical style. *Journal of Research in Music Education, 20*, 456-461.

Hagen, E. H., & Bryant, G. A. (2003). Music and dance as a colation signaling system. *Human Nature, 14*(1), 21-52.

Hall, D., Johnsrude, I., M., H., A., P., Akeroyd, M., & A., S. (2002). Spectral and temporal processing in human auditory cortex. *Cerebral Cortex, 12*, 140-149.

Halpern, A. R., & Zatorre, R. J. (1999). When that tune runs through your head: a PET investigation of auditory imagery for familiar melodies. *Cerebral Cortex, 9*, 697-704.

Halpern, A. R., Zatorre, R. J., Bouffard, M., & Johnson, J. A. (2004). Behavioral and neural correlates of perceived and imagined musical timbre. *Neuropsychologia, 42*(9), 1281-1292.

Hart, H., Palmer, A., & Hall, D. (2003). Amplitude and frequency-modulated stimuli activate common regions of human auditory cortex. *Cerebral Cortex, 13*, 773-781.

Haslinger, B., Erhard, P., Altenmüller, E., Hennenlotter, A., Schwaiger, M., Grafin von Einsiedel, H., et al. (2004). Reduced recruitment of motor association areas during bimanual coordination in concert pianists. *Human Brain Mapping, 22*(3), 206-215.

Hauser, M. D., & McDermott, J. (2003). The evolution of the music faculty: a comparative perspective. *Nature Neuroscience, 6*(7), 663-668.

Haynes, S. W. (1982). The relationship of selected high schools and student characteristics with scores achieved on the ACT assessment in the seven Great

Plains States (Doctoral dissertation). *Dissertation Abstracts International, 43*(04), 0992A.

Hebb, D. O. (1949). *The organization of behavior*. New York: Wiley.

Herscovitch, P. (1994). *Positron emission tomography - basic principles and applications to the study of auditory and language processing.* Paper presented at the 45th annual American Speech-Language Hearing Association Research Conference, New Orleans, Louisiana.

Hetland, L. (2000a). Learning to make music enhances spatial reasoning. *Journal of Aesthetic Education, 34*(3-4), 179-238.

Hetland, L. (2000b). Listening to music enhances spatial-temporal reasoning: Evidence for the "Mozart effect." *Journal of Aesthetic Education, 34*(3-4), 105-148.

Hilgetag, C. (2004). Learning from switched-off brains. *Scientific American Mind, 14,* 8-9.

Ho, Y.-C., Cheung, M.-C., & Chan, A. S. (2003). Music training improves verbal but not visual memory: Cross-sectional and longitudinal explorations in children. *Neuropsychology, 17*(3), 439-450.

Hobbs, C. (1985). A comparison of the music aptitude, scholastic aptitude, and academic achievement in young children. *Psychology of Music, 13*(2), 93-98.

Hodges, D. A. (1996a). Human musicality. In D. Hodges (Ed.), *Handbook of music psychology* (2 ed., pp. 29-68). San Antonio: IMR Press.

Hodges, D. A. (1996b). Neuromusical research: A review of the literature. In D. Hodges (Ed.), *Handbook of music psychology* (2 ed., pp. 197-284). San Antonio: IMR Press.

Hodges, D. A. (2000a). Implications of music and brain research. *Music Educator's Journal, 87*(2), 17-22.

Hodges, D. A. (2000b). A virtual panel of expert researchers. *Music Educator's Journal, 87*(2), 40-44, 60.

Hodges, D. A. (Ed.). (1996c). *Handbook of music psychology* (2 ed.). San Antonio: IMR Press.

Hodges, D. A., & O'Connell, D. (2005). *The impact of music education on academic achievement*. Retrieved October 1, 2005, from http://www.uncg.edu/mus/soundsoflearning.html

Holcomb, H., Medoff, D., Caudill, P., Zhao, Z., & Lahti, A. (1998). Cerebral blood flow relationships associated with difficult tone recognition task in trained normal volunteers. *Cerebral Cortex, 8*, 534-542.

Hose, B., Langner, G., & Scheich, H. (1987). Topographic representation of periodicities in the forebrain of the mynah bird: one map for pitch and rhythm? *Brain Research, 422*(2), 367-373.

Hubel, D. H., & Wiesel, T. N. (1970). The period of susceptibility to the physiological effects of unilateral eye closure in kittens. *Journal of Physiology, 206*, 419-436.

Hutchinson, S., Lee, L. H., Gaab, N., & Schlaug, G. (2003). Cerebellar volume of musicians. *Cerebral Cortex, 13*(9), 943-949.

Huttenlocher, P. (1979). Synaptic density in human frontal cortex: developmental changes and effects of aging. *Brain Research, 163*, 195-205.

Ibbotson, N., & Morton, J. (1981). Rhythm and dominance. *Cognition, 9*, 125-138.

Jakobson, L. S., Cuddy, L. L., & Kilgour, A. R. (2003). Time tagging: A key to musicians' superior memory. *Music Perception, 20*, 307-313.

Janata, P., Birk, J. L., Van Horn, J. D., Leman, M., Tillmann, B., & Bharucha, J. J. (2002). The cortical topography of tonal structures underlying Western music. *Science, 298*(5601), 2167-2170.

Janata, P., & Grafton, S. T. (2003). Swinging in the brain: Shared neural substrates for behaviors related to sequencing and music. *Nature Neuroscience, 6*(7), 682-687.

Jausovec, N., & Habe, K. (2005). The influence of Mozart's sonata K. 448 on brain activity during the performance of spatial rotation and numerical tasks. *Brain Topography, 17*(4), 207-218.

Jetter, J. T., & Wolff, J. L. (1985). Effect of ratio of positive and negative instances on efficiency of music concept training. *Journal of Research in Music Education, 32*, 31-43.

Johnson, C. M., & Memmott, J. E. (2006). Examination of relationships between participation in school music programs of differing quality and standardized test results. *Journal of Research in Music Education, 54*(4), 293-307.

Johnson, R. C., Bowers, J. K., Gamble, M., Lyons, F. M., Presbrey, T. W., & Vetter, R. R. (1977). Ability to transcribe music and ear superiority for tone sequences. *Cortex, 13*(3), 295-299.

Johnson, S. (2004). *Mind wide open: Your brain and the neuroscience of everyday life*. New York: Scribner.

Johnson, S. (2005). Foreword. In T. Stafford & M. Webb (Eds.), *Mind hacks: Tips and tools for using your brain*. Cambridge: O'Reilly.

Jonides, J. (2005). *The human brain*. Retrieved May 11, 2005, from http://www.umich.edu/~cogneuro/jpg/Brodmann.html

Kaas, J. H. (1991). Plasticity of sensory and motor maps in adult mammals. *Annual Review of Neuroscience, 14*, 137-167.

Kandel, E. R., & Mack, S. (2003). A parallel between radical reductionism in science and in art. *Annals of the New York Academy of Science, 1001*, 272-294.

Kandel, E. R., Schwartz, J. H., & Jessell, T. M. (Eds.). (2000). *Principles of neural science*. New York: McGraw-Hill.

Khalfa, S., Schon, D., Anton, J. L., & Liegeois-Chauvel, C. (2005). Brain regions involved in the recognition of happiness and sadness in music. *NeuroReport, 16*(18), 1981-1984.

Kilgour, A. R., Jakobson, L. S., & Cuddy, L. L. (2000). Music training and rate of presentation as mediators or text and song recall. *Memory and Cognition, 28*, 700-710.

Kimura, D. (1964). Left-right differences in the perception of melodies. *Quarterly Journal of Experimental Psychology, 16*, 355-358.

Kimura, D. (1967). Functional asymmetry of the brain in dichotic listening. *Cortex, 3*, 163-178.

Koelsch, S., Fritz, T., Schulze, K., Alsop, D., & Schlaug, G. (2005). Adults and children processing music: An fMRI study. *Neuroimage, 25*(4), 1068-1076.

Koelsch, S., Grossmann, T., Gunter, T. C., Hahne, A., Schroger, E., & Friederici, A. D. (2003). Children processing music: Electric brain responses reveal musical competence and gender differences. *Journal of Cognitive Neuroscience, 15*(5), 683-693.

Koelsch, S., Gunter, T. C., v Cramon, D. Y., Zysset, S., Lohmann, G., & Friederici, A. D. (2002). Bach speaks: A cortical "language-network" serves the processing of music. *Neuroimage, 17*(2), 956-966.

Koelsch, S., Kasper, E., Sammler, D., Schulze, K., Gunter, T., & Friederici, A. D. (2004). Music, language and meaning: Brain signatures of semantic processing. *Nature Neuroscience, 7*(3), 302-307.

Koelsch, S., & Mulder, J. (2002). Electric brain responses to inappropriate harmonies during listening to expressive music. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 113*(6), 862-869.

Kohlmetz, C., Muller, S. V., Nager, W., Münte, T. F., & Altenmüller, E. (2003). Selective loss of timbre perception for keyboard and percussion instruments following a right temporal lesion. *Neurocase, 9*(1), 86-93.

Kreutz, G., Russ, M. O., Bongard, S., & Lanfermann, H. (2003). Cerebral correlates of music listening. An fMRI-study on the effects of "happy" and "sad" classical music. *Nervenheilkunde [Nerve Medicine], 22*(3), 150-156.

Kristeva, R., Chakarova, V., Schulte-Mönting, J., & Spreer, J. (2003). Activation of cortical areas in music execution and imagining: a high-resolution EEG study. *Neuroimage, 20*(3), 1872-1883.

Kuck, H., Grossbach, M., Bangert, M., & Altenmüller, E. (2003). Brain processing of meter and rhythm in music: Electrophysiological evidence of a common network. *Annals of the New York Academy of Science, 999*, 244-253.

Kuperman, V. (2000). *Magnetic resonance imaging: Physical principles and applications*. New York: Academic Press.

Kuriki, S., Isahai, N., & Ohtsuka, A. (2005). Spatiotemporal characteristics of the neural activities processing consonant/dissonant tones in melody. *Experimental Brain Research, 162*(1), 46-55.

Langer, S. (1967). *Mind: An essay on human feeling* (Vol. 1). Baltimore: The Johns Hopkins Press.

Lauterbur, P. C. (1973). Image formation by induced local interactions: examples employing nuclear magnetic resonance. *Nature, 242*(190).

Leng, X., & Shaw, G. L. (1991). Toward a neural theory of higher brain function using music as a window. *Concepts in Neuroscience, 2*(2), 229-258.

Levitin, D. (2006). *This is your brain on music*. New York: Dutton.

Levitin, D., & Bellugi, U. (1998). Musical abilities in individuals with Williams syndrome. *Music Perception, 15*(4), 357-389.

Levitin, D., & Menon, V. (2003). Musical structure is processed in "language" areas of the brain: a possible role for Brodmann Area 47 in temporal coherence. *Neuroimage, 20*(4), 2142-2152.

Li, E., Weng, X., Han, Y., Wu, S., Zhuang, J., Chen, C., et al. (2000). Asymmetry of brain functional activation: fMRI study under language and music stimulation. *Chin Med J (Engl), 113*(2), 154-158.

Liégeois-Chauvel, C., Peretz, I., Babai, M., Laguitton, V., & Chauvel, P. (1998). Contribution of different cortical areas in the temporal lobes to music processing. *Brain, 121 ( Pt 10)*, 1853-1867.

Lints, A., & Gadbois, S. (2003). Is listening to Mozart the only way to enhance spatial reasoning? *Perceptual and Motor Skills, 97*(3 Pt 2), 1163-1174.

Lo, Y. L., & Fook-Chong, S. (2004). Ipsilateral and contralateral motor inhibitory control in musical and vocalization tasks. *Experimental Brain Research, 159*(2), 258-262.

Lo, Y. L., Fook-Chong, S., Lau, D. P., & Tan, E. K. (2003). Cortical excitability changes associated with musical tasks: a transcranial magnetic stimulation study in humans. *Neuroscience Letters, 352*(2), 85-88.

Lomax, A. (1968). *Folk song style and culture*. New Brunswick, NJ: Transaction Books.

MacLean, P. (1973). *A triune concept of the brain and behavior*. Toronto: University of Toronto Press.

Maess, B., Koelsch, S., Gunter, T. C., & Friederici, A. D. (2001). Musical syntax is processed in Broca's area: An MEG study. *Nature Neuroscience, 4*(5), 540-545.

Makris, I., & Mullet, E. (2003). Judging the pleasantness of contour-rhythm-pitch-timbre musical combinations. *The American Journal of Psychology, 116*(4), 581-611.

Maliarenko, T. N., Kuraev, G., Malyrenko, Y., Khvatova, M., Romanonva, N., & Gurina, V. (2003). The development of brain electrical activity in 4-year-old children by long-term sensory stimulation with music. *Human Physiology, 22*(1), 76-81.

Marin, O., & Perry, D. (1999). Aneurological aspects of music perception and performance. In D. Deutsch (Ed.), *The psychology of music*. San Diego: Academic.

Mark, M. (1996). *Contemporary music education* (3rd ed.). Belmont, CA: Schirmer Thomson Learning.

Mazziota, J. (1988). Brain metabolism in auditory perception: The PET study. In F. Roehmann, and F. Wilson (Ed.), *The biology of music making*. St. Louis: MMB Music.

McCaffrey, P. (2005). *The neuroscience on the web series: Neuroanatomy of speech, swallowing and language*. Retrieved May 11, 2005, from http://www.csuchico.edu/~pmccaff/syllabi/CMSD%20320/362unit4.html

Meister, I., Krings, T., Foltys, H., Boroojerdi, B., Muller, M., Topper, R., et al. (2005). Effects of long-term practice and task complexity in musicians and nonmusicians performing simple and complex motor tasks: implications for cortical motor organization. *Human Brain Mapping, 25*(3), 345-352.

Menon, V., & Levitin, D. (2005). The rewards of music listening: Response and physiological connectivity of the mesolimbic system. *Neuroimage, 28*(1), 175-184.

Merriam, A. (1964). *The anthropology of music*. Chicago: Northwestern University Press.

Meyer, L. (1956). *Emotion and meaning in music*. Chicago: University of Chicago Press.

Miller, G. F. (2000). *The mating mind*. New York: Doubleday.

Miller, L. (1989). *Musical savants: Exceptional skill and mental retardation*. Hillsdale, NJ: Laurence Erlbaum.

Minagar, A., Ragheb, J., & Kelley, R. E. (2003). The Edwin Smith surgical papyrus: Description and analysis of the earliest case of aphasia. *Journal of Medical Biography, 11*(2), 114-117.

Miyazaki, K. (1988). Musical pitch identification by absolute pitch possessors. *Perception & Psychophysics, 44*(6), 501-512.

Moss, H. (2003). Implicit selves: A review of the conference. In J. LeDoux, J. Debiec & H. Moss (Eds.), *The self: From soul to brain* (Vol. 1001, pp. 1-30). New York: The New York Academy of Sciences.

Nelson, C., & Bloom, F. (1997). Child development and neuroscience. *Child Development, 68*(5), 970-987.

Nettle, D. (2005). *Happiness: The science behind your smile*. Oxford: Oxford University Press.

Nettle, D., & Berns, G. (2005). Satisfaction and happiness. On *Science Friday* [Radio broadcast: 9/9/05]. New York: NPR.

Norton, A., Winner, E., Cronin, K., Overy, K., Lee, D. J., & Schlaug, G. (2005). Are there pre-existing neural, cognitive, or motoric markers for musical ability? *Brain Cognition, 59*(2), 124-134.

Oerter, R. (2003). Biological and psychological correlates of exceptional performance in development. *Annals of the New York Academy of Science, 999*, 451-460.

Orsmond, G. I., & Miller, L. K. (1999). Cognitive, musical and environmental correlates of early music instruction. *Psychology of Music, 27*, 18-37.

Overman, A. A., Hoge, J., Dale, J. A., Cross, J. D., & Chien, A. (2003). EEG alpha desynchronization in musicians and nonmusicians in response to changes in melody, tempo, and key in classical music. *Perceptual Motor Skills, 97*(2), 519-532.

Panksepp, J., & Bekkedal, M. Y. V. (1997). The affective cerebral consequence of music: Happy vs sad effects on the EEG and clinical implications. *International Journal of Arts Medicine, 5*(1), 18-27.

Pantev, C., Engelien, A., Candia, V., & Elbert, T. (2001). Representational cortex in musicians. Plastic alterations in response to musical practice. *Annals of the New York Academy of Science, 930*, 300-314.

Parsons, L. M. (2000). *Functional anatomy of pitch, rhythm, melody, and harmony.* Paper presented at the Mapping music in the brain: A satellite symposium of the annual conference for human brain mapping, San Antonio, Texas.

Parsons, L. M. (2001). Exploring the functional neuroanatomy of music performance, perception, and comprehension. *Annals of the New York Academy of Science, 930*, 211-231.

Parsons, L. M., & Fox, P. (1997). Sensory and cognitive tasks: The cerebellum and cognition. In J. D. Schmahmann (Ed.), *International review of neurobiology, cerebellum and cognitio*. San Diego: Academic Press.

Parsons, L. M., Sergent, J., Hodges, D. A., & Fox, P. T. (2005). The brain basis of piano performance. *Neuropsychologia, 43*(2), 199-215.

Pascual-Leone, A., Nguyet, D., Cohen, L. G., Brasil-Neto, J. P., Cammarota, A., & Hallett, M. (1995). Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. *Journal of Neurophysiology, 74*(3), 1037-1045.

Patel, A. D. (2003). Language, music, syntax and the brain. *Nature Neuroscience, 6*(7), 674-681.

Patel, A. D., Peretz, I., Tramo, M., & Labreque, R. (1998). Processing prosodic and musical patterns: A neuropsychological investigation. *Brain and Language, 61*(1), 123-144.

Penhune, V. B., Zatorre, R. J., & Evans, A. (1998). Cerebellar contributions to motor timing: A PET sutdy of auditory and visual rhythm reproduction. *Journal of Cognitive Neuroscience, 10*, 752-765.

Penhune, V. B., Zatorre, R. J., & Feindel, W. (1999). The role of auditory cortex in retention of rhythmic patterns as studied in patients with temporal lobe removals including Heschl's gyrus. *Neuropsychologia, 37*(3), 315-331.

Pepper, T. (2005, February 21). Inside the head of an applicant. *Newsweek, CXLV*.

Peretz, I. (2006). The nature of music from a biological perspective. *Cognition, 100*(1), 1-32.

Peretz, I., Ayotte, J., Zatorre, R. J., Mehler, J., Ahad, P., Penhune, V. B., et al. (2002). Congenital amusia: A disorder of fine-grained pitch discrimination. *Neuron, 33*(2), 185-191.

Peretz, I., Blood, A. J., Penhune, V. B., & Zatorre, R. J. (2001). Cortical deafness to dissonance. *Brain, 124*(Pt 5), 928-940.

Peretz, I., & Cotheart, M. (2003). Modularity of music processing. *Nature Neuroscience, 6*, 688-691.

Peretz, I., & Morais, J. (1980). Modes of processing melodies and ear asymmetry in nonmusicians. *Neuropsychologia, 18*, 477-489.

Peretz, I., & Morais, J. (1989). Music and modularity. *Contemporary Music Review, 4*, 277-291.

Peretz, I., & Zatorre, R. J. (2003). *The cognitive neuroscience of music*. Oxford: Oxford University Press.

Peretz, I., & Zatorre, R. J. (2005). Brain organization for music processing. *Annual Review of Psychology, 56*, 89-114.

Piaget, J. (1950). *The psychology of intelligence*. London: Routledge and Kegan Paul.

Pinker, S. (1997). *How the mind works*. New York: W. W. Norton & Company, Inc.

Platel, H., Baron, J. C., Desgranges, B., Bernard, F., & Eustache, F. (2003). Semantic and episodic memory of music are subserved by distinct neural networks. *Neuroimage, 20*(1), 244-256.

Platel, H., Price, C., Baron, J. C., Wise, R., Lambert, J., Frackowiak, R. S., et al. (1997). The structural components of music perception. A functional anatomical study. *Brain, 120 ( Pt 2)*, 229-243.

Popescu, M., Otsuka, A., & Ioannides, A. A. (2004). Dynamics of brain activity in motor and frontal cortical areas during music listening: a magnetoencephalographic study. *Neuroimage, 21*(4), 1622-1638.

Posner, M., & Raichle, M. (1994). *Images of mind*. New York: Scientific American Library.

Price, H. E. (1999). Forum. *Journal of Research in Music Education, 47*(3), 196-197.

Ramachandran, V., & Blakeslee, S. (1998). *Phantoms in the brain: Probing the mysteries of the human mind*. New York: HarperCollins.

Ratey, J. (2001). *A user's guide to the brain*. New York: Vintage Books.

Rauscher, F. H., Shaw, G. L., & Ky, K. N. (1993). Music and spatial task performance. *Nature, 365*, 611.

Reimer, B. (1989). *A philosophy of music education* (2 ed.). Englewood Cliffs, NJ: Prentice-Hall.

Restak, R. (1994). *The modular brain*. New York: Scribner.

Roberts, L. (1989). Are neural nets like the human brain? *Science, 243*(4890), 481-482.

Roederer, J. (1982). Physical and neuropsychological foundations of music: The basic questions. In M. Clynes (Ed.), *Music, mind, and brain: The neuropsychology of music*. New York: Plenum Press.

Rolls, E. (1989). The representation and storage of information in neuronal networks in the primate cerebral cortex and hippocampus. In R. Durbin, C. Miall & G. Mitchison (Eds.), *The computing neuron*. New York: Addison-Wesley.

Rosenthal, R. K. (1984). The relative effects of guided model, model only, guide only, and practice only treatments on the accuracy of advanced instrumentalists' musical performance. *Journal of Research in Music Education, 32*, 265-274.

Ross, D. A., Olson, I. R., & Gore, J. C. (2003). Cortical plasticity in an early blind musician: An fMRl study. *Magnetic Resonance Imaging, 21*(7), 821-828.

Saffran, J. R. (2003). Musical learning and language development. *Annals of the New York Academy of Science, 999*, 397-401.

Sakai, K., Hikosaka, O., Miyauchi, S., Takino, R., Tamada, T., Iwata, N. K., et al. (1999). Neural representation of a rhythm depends on its interval ratio. *Journal of Neuroscience, 19*(22), 10074-10081.

Sang, R. C. (1987). A study of the relationship between instrumental music teachers' modeling skills and pupil performance behaviors. *Bulletin of the Council for Research in Music Education, 43*, 313-329.

Satoh, M., Takeda, K., Nagata, K., Hatazawa, J., & Kuzuhara, S. (2003). The anterior portion of the bilateral temporal lobes participates in music perception: a positron emission tomography study. *AJNR. American Journal of Neuroradiology, 24*(9), 1843-1848.

Schlaug, G. (2001). The brain of musicians: A model for functional and structural changes. *Annals of the New York Academy of Science, 930*, 281-299.

Schlaug, G., Jäncke, L., Huang, Y., Staiger, J., & Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia, 33*, 1047-1055.

Schlaug, G., Jäncke, L., Huang, Y., & Steinmetz, H. (1994). *In vivo morphometry of interhemispheric asymmetry and connectivity in musicians.* Paper presented at the 3rd international conference for music perception and cognition, Liege, Belgium.

Schlaug, G., Jäncke, L., Huang, Y., & Steinmetz, H. (1995). In vivo evidence of structural brain asymmetry in musicians. *Science, 267*(5198), 699-701.

Schlaug, G., Norton, A., Overy, K., & Winner, E. (2005). Effects of music training on the child's brain and cognitive development. *Annals of the New York Academy of Science, 1060*, 219-230.

Schmidt, L. A., & Trainor, L. J. (2001). Frontal brain electrical activity (EEG) distinguishes valence and intensity of musical emotions. *Cognition & Emotion, 15*(4), 487-500.

Schmithorst, V. J., & Holland, S. K. (2004). The effect of musical training on the neural correlates of math processing: a functional magnetic resonance imaging study in humans. *Neuroscience Letters, 354*(3), 193-196.

Schneider, P., Sluming, V., Roberts, N., Scherg, M., Goebel, R., Specht, H. J., et al. (2005). Structural and functional asymmetry of lateral Heschl's gyrus reflects pitch perception preference. *Nature Neuroscience, 8*(9), 1241-1247.

Schon, D., Magne, C., & Besson, M. (2004). The music of speech: Music training facilitates pitch processing in both music and language. *Psychophysiology, 41*(3), 341-349.

Selby, B., Rosenfeld, J., Styles, E., & Westcott, J. (1982). Which hemisphere is trained? The need for a new strategy for interpreting hemispheric asymmetries in music perception. *Psychology of Music, special issue*, 101-103.

Sergent, J. (1993). Mapping the musician brain. *Human Brain Mapping, 1*(1), 20-38.

Seung, Y., Kyong, J. S., Woo, S. H., Lee, B. T., & Lee, K. M. (2005). Brain activation during music listening in individuals with or without prior music training. *Neuroscience Research, 52*(4), 323-329.

Shahin, A., Bosnyak, D. J., Trainor, L. J., & Roberts, L. E. (2003). Enhancement of neuroplastic P2 and N1c auditory evoked potentials in musicians. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 23*(13), 5545-5552.

Shallice, T. (2003). Functional imaging and neuropsychology findings: How can they be linked? *Neuroimage, 20*, 146-154.

Shaw, G. L. (2000). *Keeping Mozart in mind*. San Diego: Academic Press.

Shepherd, G. (1990). *The synaptic organization of the brain* (3 ed.). New York: Oxford.

Shepherd, G. (1994). *Neurobiology*. New York: Oxford University Press.

Sluming, V., Barrick, T., Howard, M., Cezayirli, E., Mayes, A., & Roberts, N. (2002). Voxel-based morphometry reveals increased gray matter density in Broca's area in male symphony orchestra musicians. *Neuroimage, 17*(3), 1613-1622.

Spintge, R., & Droh, R. (1992). *MusicMedicine* (Vol. 1). St. Louis, MO: MMB Music.

Stafford, T., & Webb, M. (2005). *Mind hacks: Tips and tools for using your brain*. Cambridge: O'Reilly.

Steele, K. M., Brown, J. D., & Stoecker, J. A. (1999). Failure to confirm the Rauscher and Shaw description of recovery of the Mozart effect. *Perceptual and Motor Skills, 88*(3 Pt 1), 843-848.

Stephens, G. L., & Graham, G. (2000). *When self-consciousness breaks*. Cambridge, MA: MIT Press.

Stiles, J. (2000). Neural plasticity and cognitive development. *Developmental Neuropsychology, 18*(2), 237-272.

Stillings, N., Weisler, S., Chase, C., Feinstein, M., Garfield, J., & Rissland., E. (1995). *Cognitive science: An introduction* (2 ed.). Cambridge, MA: Bradford.

Sutoo, D., & Akiyama, K. (2004). Music improves dopaminergic neurotransmission: demonstration based on the effect of music on blood pressure regulation. *Brain Research, 1016*(2), 255-262.

Sylwester, R. (1995). *A celebration of neurons: An educator's guide to the human brain*. Alexandria, VA: Association for Supervision and curriculum Development.

Takeuchi, A., & Hulse, S. (1993). Absolute pitch. *Psychological Bulletin, 113*, 345-361.

Tanioka, F., Takazawa, T., Kamata, S., Kudo, M., Matsuki, A., & Oyama, T. (1987). Hormonal effect of anxiolytic music in patients during surgical operations under epidural anesthesia. In R. Spintge & R. Droh (Eds.), *Music in medicine*. Berlin: Springer-Verlag.

Tervaniemi, M., Medvedev, S. V., Alho, K., Pakhomov, S. V., Roudas, M. S., Van Zuijen, T. L., et al. (2000). Lateralized automatic auditory processing of phonetic versus musical information: a PET study. *Hum Brain Mapp, 10*(2), 74-79.

Thivard, L., Belin, P., Zibovicius, M., Poline, J., & Samson, Y. (2000). A cortical region sensitive to auditory spectral motion. *NeuroReport, 11*, 2969-2972.

Trainor, L. J., Shahin, A., & Roberts, L. E. (2003). Effects of musical training on the auditory cortex in children. *Annals of the New York Academy of Science, 999*, 506-513.

Tsao, C. C., Gordon, T. F., Maranto, C. D., Lerman, C., & Murasko, D. (1991). The effects of music and directed biological imagery on immune response S-IgA. In M. C. D. (Ed.), *Applications of music in medicine*. Washington, D. C.: National Association for Music Therapy.

Tzourio, N., Nkanga-Ngila, B., & Mazoyer, B. (1998). Left planum temporale surface correlates with functional dominance during story listening. *NeuroReport, 9*, 829-833.

Vaughn, K. (2000). Music and mathematics: Modest support for the oft-claimed relationship. *Journal of Aesthetic Education, 34*(3-4), 149-166.

Vollmer-Haase, J., Finke, K., Hartje, W., & Bulla-Hellwig, M. (1998). Hemispheric dominance in the processing of J.S. Bach fugues: a transcranial Doppler sonography (TCD) study with musicians. *Neuropsychologia, 36*(9), 857-867.

Vuust, P., Pallesen, K. J., Bailey, C., van Zuijen, T. L., Gjedde, A., Roepstorff, A., et al. (2005). To musicians, the message is in the meter pre-attentive neuronal responses to incongruent rhythm are left-lateralized in musicians. *Neuroimage, 24*(2), 560-564.

Wagner, M., & Hannon, R. (1981). The effect of music listening and attentiveness training on the EEG's of musicians and nonmusicians. *Journal of Music Therapy, 14*, 151-164.

Wallin, N. L., Merker, B., & Brown, S. (2000). *The origins of music*. Cambridge, MA: MIT Press.

Ward, W. (1999). Absolute pitch. In D. Deutsch (Ed.), *The psychology of music* (2nd ed.). New York: Academic.

Warrier, C. M., & Zatorre, R. J. (2004). Right temporal cortex is critical for utilization of melodic contextual cues in a pitch constancy task. *Brain, 127*(Pt 7), 1616-1625.

Wilson, F. (1986). *Tone deaf and all thumbs*. New York: Viking.

Wilson, S. J., Pressing, J. L., & Wales, R. J. (2002). Modeling rhythmic function in a musician post-stroke. *Neuropsychologia, 40*(8), 1494-1505.

Yoo, S., Lee, C., & Choi, B. (2001). Human brain mapping of auditory imagery; event-related functional MRI study. *NeuroReport, 12*, 3045-3049.

Zatorre, R. J. (2003). Music and the brain. *Annals of the New York Academy of Science, 999*, 4-14.

Zatorre, R. J., & Belin, P. (2001). Spectral and temporal processing in human auditory cortex. *Cerebral Cortex, 11*(10), 946-953.

Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: Music and speech. *Trends in Cognitive Sciences, 6*(1), 37-46.

Zatorre, R. J., Halpern, A. R., Perry, D., Meyer, E., & Evans, A. (1996). Hearing in the mind's ear: A PET investigation of musical imagery and perception. *Journal of Cognitive Neuroscience, 8*(1), 29-46.

Zatorre, R. J., & McGill, J. (2005). Music, the food of neuroscience? *Nature, 434*(7031), 312-315.

Zatorre, R. J., & Samson, S. (1991). Role of the right temporal neocortex in retention of pitch in auditory short-term memory. *Brain, 114*(Pt. 6), 2403-2417.

# APPENDIX A

## *MusicBIRD* REFERENCES

The references below represent the studies included in the *MusicBIRD* as of 1/14/08


Abbott, A. (2002). Music, maestro, please! *Nature, 416*(6876), 12-14.

Alkon, D. (1989). Memory storage and neural systems. *Scientific American, 261*(1), 42-50.

Altenmüller, E. O. (2001). How many music centers are in the brain? *Annals of the New York Academy of Science, 930*, 273-280.

Arfel, G., Casanova, C., & Coulmance, M. (1969). [Dynamic aspects of the human electroencephalogram. 1st results of a radio-telemetric study]. *Electroencephalography and Clinical Neurophysiology, 27*(3), 225-237.

Arnadottis, G. (1990). *The brain and behavior*. St. Louis: C. B. Mosby.

Baharloo, S., Service, S., & Risch, N. (2000). Familial aggregation of absolute pitch. *The American Journal of Human Genetics, 67*, 755-758.

Bangert, M., & Altenmüller, E. O. (2003). Mapping perception to action in piano practice: a longitudinal DC-EEG study. *BMC Neuroscience, 4*(26), 14.

Barrett, D. L. (1993). Relationship of musical audiation to musical training, musical proficiency and scholastic achievement among advantaged and disadvantaged 6-to-8 year olds. (Doctoral dissertation, Columbia University Teachers College). *Dissertation Abstracts International, 54*(12), 4383A.

Bartlett, D. (1996). Physiological responses to music and sound stimuli. In D. Hodges (Ed.), *Handbook of music psychology* (2nd ed.). University of San Antonio: IMR Press.

Bartlett, D., Kaufman, D., & Smeltekop, R. (1993). The effects of music listening and perceived sensory experiences on the immune system as measured by interleukin-1 and cortisol. *Journal of Music Therapy, 30*(4), 194-209.

Bengtsson, S. L., & Ullen, F. (2006). Dissociation between melodic and rhythmic processing during piano performance from musical scores. *Neuroimage, 30*(1), 272-284.

Berns, G. (2005). *Satisfaction: The science of finding true fulfillment*. New York: Henry Holt.

Besson, M., & Faïta, F. (1995). An event-related potential (ERP) study of musical expectancy: comparison of musicians with nonmusicians. *Journal of Experimental Pscyhology: Human Perception, 21*, 1278-1296.

Besson, M., Faita, F., & Requin, J. (1994). Brain waves associated with musical incongruities differ for musicians and non-musicians. *Neuroscience Letters, 168*(1-2), 101-105.

Blacking, J. (1973). *How musical is man?* Seattle: University of Washington Press.

Blackwell, L., Trzesniewski, K., & Dweck, C. S. (2007). Implicit Theories of Intelligence Predict Achievement across an Adolescent Transition: A Longitudinal Study and an Intervention. *Child Development, 78*(1), 246-263.

Blood, A., & Zatorre, R. J. (2001). Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *Proceedings of the National Academy of Sciences of the United States of America, 98*(II), 818-823.

Bloom, F., Lazerson, A., & Hofstadter, l. (1985). *Brain, mind, and behavior*. New York: Freeman.

Blumstein, S., Goodglass, H., & Tartter, V. (1975). The reliability of ear advantage in dichotic listening. *Brain and Language, 2*, 226-236.

Booth, J. N., Koren, S. A., & Persinger, M. A. (2005). Increased feelings of the sensed presence and increased geomagnetic activity at the time of the experience during exposures to transcerebral weak complex magnetic fields. *International Journal of Neuroscience, 115*(7), 1053-1079.

Bryden, M. (1963). Ear preferences in auditory perception. *Journal of Experimental Psychology, 65*, 103-105.

Bunzeck, N., Wuestenberg, T., Lutz, K., Heinze, H. J., & Jäncke, L. (2005). Scanning silence: mental imagery of complex sounds. *Neuroimage, 26*(4), 1119-1127.

Butzlaff, R. (2000). Can music be used to teach reading? *Journal of Aesthetic Education, 34*(3-4), 167-178.

Byo, J. L. (1990). Recognition of intensity contrasts in gestures of beginning conductors. *Journal of Research in Music Education, 38*, 157-163.

Carey, B. (2005, October 18, 2005). Can brain scans see depression? *The New York Times*.

Carter, R., & Frith, C. (1998). *Mapping the mind*. Los Angeles: University of California Press.

Chan, A. S., Ho, Y.-C., & Cheung, M. C. (1998). Music training improves verbal memory. *Nature, 396*, 128-129.

Chomsky, N. (1986). *Knowledge of language: Its nature, origin, and use*. New York: Praeger.

Churchland, P. (1993). *Matter and consciousness* (Rev. ed.). Cambridge: MIT Press.

Churchland, P. (2003). *Self-representation in nervous systems* (Vol. 1001). New York: The New York Academy of Sciences.

Ciepluch, G. M. (1988). Sightreading achievement in instrumental music performance, learning gifts, and academic achievement: a correlation study. (Doctoral dissertation, The University of Wisconsin - Madison). *Dissertation Abstracts International, 49*(06), 1398A.

Cui, H. W., Zhang, S. Z., Di, H. B., Liu, H., Zhu, Y. H., Zhang, Q. W., et al. (2005). [Functional MRI of human brain in musicians and non-musicians]. *Zhejiang Da Xue Xue Bao Yi Xue Ban, 34*(4), 326-330.

Curtiss, S. (1977). *Genie: A psycholinguistic study of a modern-day "wild child"*. New York: Academic Press.

Darwin, C. (1871). *The origin of species*. New York: Modern Library.

DaSilva, A. F., Tuch, D. S., Wiegell, M. R., & Hadjikhani, N. (2003). A primer on diffusion tensor imaging of anatomical substructures. *Neurosurgical Focus, 15*(1), E4.

Demorest, S. (2000). Does music make you smarter? *Music Educator's Journal, 87*(2), 33-39, 58.

Deutsch, D. (1999). *The psychology of music* (2nd ed.). New York: Academic Press.

Deutsch, D., Henthorn, T., & Dolson, M. (2004). Absolute pitch, speech, and tone language: Some experiments and a proposed framework. *Music Perception, 21*(3), 339.

Di Pietro, M., Laganaro, M., Leemann, B., & Schnider, A. (2004). Receptive amusia: temporal auditory processing deficit in a professional musician following a left temporo-parietal lesion. *Neuropsychologia, 42*(7), 868-877.

Dowling, W. J. (1988). Tonal structure and children's early learning of music. In J. Sloboda (Ed.), *Generative processes in music* (pp. 113-128). Oxford: Clarendon Press.

Drayna, D., Manichaikul, A., de Lange, M., Snieder, H., & Spector, T. (2001). Genetic correlates of musical pitch recognition in humans. *Science, 291*, 1969-1971.

Drennan, C. B. (1984). The relationship of musical aptitude, academic achievement and intelligence in merit (gifted) students of Murfreesboro City Schools (Tennessee). (Doctoral dissertation, Tennessee State University). *Dissertation Abstracts International, 46*(12), 3581A.

Drubach, D. (2000). *The brain explained*. Upper Saddle River, NJ: Prentice Hall Health.

Dubos, R. (1981). *Celebrations of life*. New York: McGraw-Hill.

Duke, R. A., Flowers, P. J., & Wolfe, D. E. (1997). Children who study piano with excellent teachers in the United States. *Bulletin of the Council for Research in Music Education, 132*, 51-84.

Edmister, W. B., Talavage, T. M., Ledden, P. J., & Weisskoff, R. M. (1999). Improved auditory cortex imaging using clustered volume acquisitions. *Human Brain Mapping, 7*(2), 89-97.

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., & Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science, 270*(5234), 305-307.

Epstein, H. (1978). Growth spurts during brain development: Implications for educational policy and practice. In J. Chall & A. Mirsky (Eds.), *Education and the brain*. Chicago: University of Chicago Press.

Epstein, H. (1986). Stages in human brain development. *Developmental Brain Research, 30*, 114-119.

Evers, S., & Suhr, B. (2000). Changes of the neurotransmitter serotonin but not of hormones during short time music perception. *European Archives of Psychiatry and Clinical Neuroscience, 250*(3), 144-147.

Flohr, J., & Hodges, D. A. (2002). Music and neuroscience. In R. Colwell & C. Richardson (Eds.), *The New Handbook of Research on Music Teaching and Learning* (pp. 991-1008). New York: Oxford University Press.

Flohr, J., Persellin, D., & Miller, D. (1996). *Children's electrophysical responses to music.* Paper presented at the 22nd International Society for Music Education World Conference, Amsterdam, The Netherlands.

Fox, D. (2000). Music and the baby's brain: Early experiences. *Music Educator's Journal, 87*(2), 23-27, 50.

Fox, P., Sergent, J., Hodges, D. A., Martin, C., Jerabek, P., Glass, T., et al. (1995). *Piano performance from memory: A PET study.* Paper presented at the Human Brain Mapping Conference, Paris.

Fries, W., & Swihart, A. A. (1990). Disturbance of rhythm sense following right hemisphere damage. *Neuropsychologia, 28*(12), 1317-1323.

Frisina, R. D. (2001). Subcortical neural coding mechanisms for auditory temporal processing. *Hearing Research, 158*(1-2), 1-27.

Fujioka, T., Trainor, L. J., Ross, B., Kakigi, R., & Pantev, C. (2004). Musical training enhances automatic encoding of melodic contour and interval structure. *Journal of Cognitive Neuroscience, 16*(6), 1010-1021.

Gaab, N., Gaser, C., Zaehle, T., Janäcke, L., & Schlaug, G. (2003). Functional anatomy of pitch memory: an fMRI study with sparse temporal sampling. *Neuroimage, 19*, 1417-1426.

Gardner, H. (1983). *Frames of mind: The theory of multiple intelligences*. New York: BasicBooks.

Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. *Journal of Neuroscience, 23*(27), 9240-9245.

Gaston, E. T. (1968). Factors contributing to responses in music. In E. T. Gaston (Ed.), *Music Therapy*. Lawerence, KS: Allen Press.

Gazzaniga, M. (2005). *The ethical brain*. New York: Dana Press.

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., et al. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences of the United States of America, 101*(21), 8174-8179.

Graziano, A. B., Peterson, M., & Shaw, G. (1999). Enhanced learning of proportional math through music training and spatial-temporal training. *Neurological Research, 21*, 139-152.

Greenough, W. T. (1984). Possible structural substrates of plastic neural phenomena. In G. Lynch, J. L. McGaugh & N. M. Weinberger (Eds.), *Neurobiology of Learning and Memory* (pp. 470-478). New York: Guilford Press.

Gregersen, P., Kowalsky, E., Kohn, N., & Marvin, E. (2000). Early childhood music education and predisposition to absolute pitch: teasing apart genes and environment. *The American Journal of Human Genetics, 98*, 280-282.

Gruhn, F., & Rauscher, F. H. (Eds.). (2007). *Neurosciences in music pedagogy*: Nova Science Publishers.

Gulick, W., Gescheider, G., & Frisina, R. (1989). *Hearing: Physiological acoustics, neural coding, and psychoacoustics*. New York: Oxford University Press.

Haack, P. A. (1972). Use of positive and negative examples in teaching the concept of musical style. *Journal of Research in Music Education, 20*, 456-461.

Hagen, E. H., & Bryant, G. A. (2003). Music and dance as a colation signaling system. *Human Nature, 14*(1), 21-52.

Hall, D., Johnsrude, I., M., H., A., P., Akeroyd, M., & A., S. (2002). Spectral and temporal processing in human auditory cortex. *Cerebral Cortex, 12*, 140-149.

Halpern, A. R., & Zatorre, R. J. (1999). When that tune runs through your head: a PET investigation of auditory imagery for familiar melodies. *Cerebral Cortex, 9*, 697-704.

Halpern, A. R., Zatorre, R. J., Bouffard, M., & Johnson, J. A. (2004). Behavioral and neural correlates of perceived and imagined musical timbre. *Neuropsychologia, 42*(9), 1281-1292.

Hart, H., Palmer, A., & Hall, D. (2003). Amplitude and frequency-modulated stimuli activate common regions of human auditory cortex. *Cerebral Cortex, 13*, 773-781.

Haslinger, B., Erhard, P., Altenmüller, E., Hennenlotter, A., Schwaiger, M., Grafin von Einsiedel, H., et al. (2004). Reduced recruitment of motor association areas during bimanual coordination in concert pianists. *Human Brain Mapping, 22*(3), 206-215.

Hauser, M. D., & McDermott, J. (2003). The evolution of the music faculty: a comparative perspective. *Nature Neuroscience, 6*(7), 663-668.

Haynes, S. W. (1982). The relationship of selected high schools and student characteristics with scores achieved on the ACT assessment in the seven Great Plains States (Doctoral dissertation). *Dissertation Abstracts International, 43*(04), 0992A.

Hebb, D. O. (1949). *The organization of behavior*. New York: Wiley.

Herscovitch, P. (1994). *Positron emission tomography - basic principles and applications to the study of auditory and language processing.* Paper presented at the 45th annual American Speech-Language Hearing Association Research Conference, New Orleans, Louisiana.

Hetland, L. (2000a). Learning to make music enhances spatial reasoning. *Journal of Aesthetic Education, 34*(3-4), 179-238.

Hetland, L. (2000b). Listening to music enhances spatial-temporal reasoning: Evidence for the "Mozart effect." *Journal of Aesthetic Education, 34*(3-4), 105-148.

Hilgetag, C. (2004). Learning from switched-off brains. *Scientific American Mind, 14,* 8-9.

Ho, Y.-C., Cheung, M.-C., & Chan, A. S. (2003). Music training improves verbal but not visual memory: Cross-sectional and longitudinal explorations in children. *Neuropsychology, 17*(3), 439-450.

Hobbs, C. (1985). A comparison of the music aptitude, scholastic aptitude, and academic achievement in young children. *Psychology of Music, 13*(2), 93-98.

Hodges, D. A. (1996a). Human musicality. In D. Hodges (Ed.), *Handbook of music psychology* (2 ed., pp. 29-68). San Antonio: IMR Press.

Hodges, D. A. (1996b). Neuromusical research: A review of the literature. In D. Hodges (Ed.), *Handbook of music psychology* (2 ed., pp. 197-284). San Antonio: IMR Press.

Hodges, D. A. (2000a). Implications of music and brain research. *Music Educator's Journal, 87*(2), 17-22.

Hodges, D. A. (2000b). A virtual panel of expert researchers. *Music Educator's Journal, 87*(2), 40-44, 60.

Hodges, D. A. (Ed.). (1996c). *Handbook of music psychology* (2 ed.). San Antonio: IMR Press.

Hodges, D. A., & O'Connell, D. (2005). *The impact of music education on academic achievement*. Retrieved October 1, 2005, from http://www.uncg.edu/mus/soundsoflearning.html

Holcomb, H., Medoff, D., Caudill, P., Zhao, Z., & Lahti, A. (1998). Cerebral blood flow relationships associated with difficult tone recognition task in trained normal volunteers. *Cerebral Cortex, 8*, 534-542.

Hose, B., Langner, G., & Scheich, H. (1987). Topographic representation of periodicities in the forebrain of the mynah bird: one map for pitch and rhythm? *Brain Research, 422*(2), 367-373.

Hubel, D. H., & Wiesel, T. N. (1970). The period of susceptibility to the physiological effects of unilateral eye closure in kittens. *Journal of Physiology, 206*, 419-436.

Hutchinson, S., Lee, L. H., Gaab, N., & Schlaug, G. (2003). Cerebellar volume of musicians. *Cerebral Cortex, 13*(9), 943-949.

Huttenlocher, P. (1979). Synaptic density in human frontal cortex: developmental changes and effects of aging. *Brain Research, 163*, 195-205.

Ibbotson, N., & Morton, J. (1981). Rhythm and dominance. *Cognition, 9*, 125-138.

Jakobson, L. S., Cuddy, L. L., & Kilgour, A. R. (2003). Time tagging: A key to musicians' superior memory. *Music Perception, 20*, 307-313.

Janata, P., Birk, J. L., Van Horn, J. D., Leman, M., Tillmann, B., & Bharucha, J. J. (2002). The cortical topography of tonal structures underlying Western music. *Science, 298*(5601), 2167-2170.

Janata, P., & Grafton, S. T. (2003). Swinging in the brain: Shared neural substrates for behaviors related to sequencing and music. *Nature Neuroscience, 6*(7), 682-687.

Jausovec, N., & Habe, K. (2005). The influence of Mozart's sonata K. 448 on brain activity during the performance of spatial rotation and numerical tasks. *Brain Topography, 17*(4), 207-218.

Jetter, J. T., & Wolff, J. L. (1985). Effect of ratio of positive and negative instances on efficiency of music concept training. *Journal of Research in Music Education, 32*, 31-43.

Johnson, C. M., & Memmott, J. E. (2006). Examination of relationships between participation in school music programs of differing quality and standardized test results. *Journal of Research in Music Education, 54*(4), 293-307.

Johnson, R. C., Bowers, J. K., Gamble, M., Lyons, F. M., Presbrey, T. W., & Vetter, R. R. (1977). Ability to transcribe music and ear superiority for tone sequences. *Cortex, 13*(3), 295-299.

Johnson, S. (2004). *Mind wide open: Your brain and the neuroscience of everyday life*. New York: Scribner.

Johnson, S. (2005). Foreword. In T. Stafford & M. Webb (Eds.), *Mind hacks: Tips and tools for using your brain*. Cambridge: O'Reilly.

Jonides, J. (2005). *The human brain*. Retrieved May 11, 2005, from http://www.umich.edu/~cogneuro/jpg/Brodmann.html

Kaas, J. H. (1991). Plasticity of sensory and motor maps in adult mammals. *Annual Review of Neuroscience, 14*, 137-167.

Kandel, E. R., & Mack, S. (2003). A parallel between radical reductionism in science and in art. *Annals of the New York Academy of Science, 1001*, 272-294.

Kandel, E. R., Schwartz, J. H., & Jessell, T. M. (Eds.). (2000). *Principles of neural science*. New York: McGraw-Hill.

Khalfa, S., Schon, D., Anton, J. L., & Liegeois-Chauvel, C. (2005). Brain regions involved in the recognition of happiness and sadness in music. *NeuroReport, 16*(18), 1981-1984.

Kilgour, A. R., Jakobson, L. S., & Cuddy, L. L. (2000). Music training and rate of presentation as mediators or text and song recall. *Memory and Cognition, 28*, 700-710.

Kimura, D. (1964). Left-right differences in the perception of melodies. *Quarterly Journal of Experimental Psychology, 16*, 355-358.

Kimura, D. (1967). Functional asymmetry of the brain in dichotic listening. *Cortex, 3*, 163-178.

Koelsch, S., Fritz, T., Schulze, K., Alsop, D., & Schlaug, G. (2005). Adults and children processing music: An fMRI study. *Neuroimage, 25*(4), 1068-1076.

Koelsch, S., Grossmann, T., Gunter, T. C., Hahne, A., Schroger, E., & Friederici, A. D. (2003). Children processing music: Electric brain responses reveal musical competence and gender differences. *Journal of Cognitive Neuroscience, 15*(5), 683-693.

Koelsch, S., Gunter, T. C., v Cramon, D. Y., Zysset, S., Lohmann, G., & Friederici, A. D. (2002). Bach speaks: A cortical "language-network" serves the processing of music. *Neuroimage, 17*(2), 956-966.

Koelsch, S., Kasper, E., Sammler, D., Schulze, K., Gunter, T., & Friederici, A. D. (2004). Music, language and meaning: Brain signatures of semantic processing. *Nature Neuroscience, 7*(3), 302-307.

Koelsch, S., & Mulder, J. (2002). Electric brain responses to inappropriate harmonies during listening to expressive music. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 113*(6), 862-869.

Kohlmetz, C., Muller, S. V., Nager, W., Münte, T. F., & Altenmüller, E. (2003). Selective loss of timbre perception for keyboard and percussion instruments following a right temporal lesion. *Neurocase, 9*(1), 86-93.

Kreutz, G., Russ, M. O., Bongard, S., & Lanfermann, H. (2003). Cerebral correlates of music listening. An fMRI-study on the effects of "happy" and "sad" classical music. *Nervenheilkunde [Nerve Medicine], 22*(3), 150-156.

Kristeva, R., Chakarova, V., Schulte-Mönting, J., & Spreer, J. (2003). Activation of cortical areas in music execution and imagining: a high-resolution EEG study. *Neuroimage, 20*(3), 1872-1883.

Kuck, H., Grossbach, M., Bangert, M., & Altenmüller, E. (2003). Brain processing of meter and rhythm in music: Electrophysiological evidence of a common network. *Annals of the New York Academy of Science, 999*, 244-253.

Kuperman, V. (2000). *Magnetic resonance imaging: Physical principles and applications*. New York: Academic Press.

Kuriki, S., Isahai, N., & Ohtsuka, A. (2005). Spatiotemporal characteristics of the neural activities processing consonant/dissonant tones in melody. *Experimental Brain Research, 162*(1), 46-55.

Langer, S. (1967). *Mind: An essay on human feeling* (Vol. 1). Baltimore: The Johns Hopkins Press.

Lauterbur, P. C. (1973). Image formation by induced local interactions: examples employing nuclear magnetic resonance. *Nature, 242*(190).

Leng, X., & Shaw, G. L. (1991). Toward a neural theory of higher brain function using music as a window. *Concepts in Neuroscience, 2*(2), 229-258.

Levitin, D. (2006). *This is your brain on music*. New York: Dutton.

Levitin, D., & Bellugi, U. (1998). Musical abilities in individuals with Williams syndrome. *Music Perception, 15*(4), 357-389.

Levitin, D., & Menon, V. (2003). Musical structure is processed in "language" areas of the brain: a possible role for Brodmann Area 47 in temporal coherence. *Neuroimage, 20*(4), 2142-2152.

Li, E., Weng, X., Han, Y., Wu, S., Zhuang, J., Chen, C., et al. (2000). Asymmetry of brain functional activation: fMRI study under language and music stimulation. *Chin Med J (Engl), 113*(2), 154-158.

Liégeois-Chauvel, C., Peretz, I., Babai, M., Laguitton, V., & Chauvel, P. (1998). Contribution of different cortical areas in the temporal lobes to music processing. *Brain, 121 ( Pt 10)*, 1853-1867.

Lints, A., & Gadbois, S. (2003). Is listening to Mozart the only way to enhance spatial reasoning? *Perceptual and Motor Skills, 97*(3 Pt 2), 1163-1174.

Lo, Y. L., & Fook-Chong, S. (2004). Ipsilateral and contralateral motor inhibitory control in musical and vocalization tasks. *Experimental Brain Research, 159*(2), 258-262.

Lo, Y. L., Fook-Chong, S., Lau, D. P., & Tan, E. K. (2003). Cortical excitability changes associated with musical tasks: a transcranial magnetic stimulation study in humans. *Neuroscience Letters, 352*(2), 85-88.

Lomax, A. (1968). *Folk song style and culture*. New Brunswick, NJ: Transaction Books.

MacLean, P. (1973). *A triune concept of the brain and behavior*. Toronto: University of Toronto Press.

Maess, B., Koelsch, S., Gunter, T. C., & Friederici, A. D. (2001). Musical syntax is processed in Broca's area: An MEG study. *Nature Neuroscience, 4*(5), 540-545.

Makris, I., & Mullet, E. (2003). Judging the pleasantness of contour-rhythm-pitch-timbre musical combinations. *The American Journal of Psychology, 116*(4), 581-611.

Maliarenko, T. N., Kuraev, G., Malyrenko, Y., Khvatova, M., Romanonva, N., & Gurina, V. (2003). The development of brain electrical activity in 4-year-old children by long-term sensory stimulation with music. *Human Physiology, 22*(1), 76-81.

Marin, O., & Perry, D. (1999). Aneurological aspects of music perception and performance. In D. Deutsch (Ed.), *The psychology of music*. San Diego: Academic.

Mark, M. (1996). *Contemporary music education* (3rd ed.). Belmont, CA: Schirmer Thomson Learning.

Mazziota, J. (1988). Brain metabolism in auditory perception: The PET study. In F. Roehmann, and F. Wilson (Ed.), *The biology of music making*. St. Louis: MMB Music.

McCaffrey, P. (2005). *The neuroscience on the web series: Neuroanatomy of speech, swallowing and language*. Retrieved May 11, 2005, from http://www.csuchico.edu/~pmccaff/syllabi/CMSD%20320/362unit4.html

Meister, I., Krings, T., Foltys, H., Boroojerdi, B., Muller, M., Topper, R., et al. (2005). Effects of long-term practice and task complexity in musicians and nonmusicians performing simple and complex motor tasks: implications for cortical motor organization. *Human Brain Mapping, 25*(3), 345-352.

Menon, V., & Levitin, D. (2005). The rewards of music listening: Response and physiological connectivity of the mesolimbic system. *Neuroimage, 28*(1), 175-184.

Merriam, A. (1964). *The anthropology of music*. Chicago: Northwestern University Press.

Meyer, L. (1956). *Emotion and meaning in music*. Chicago: University of Chicago Press.

Miller, G. F. (2000). *The mating mind*. New York: Doubleday.

Miller, L. (1989). *Musical savants: Exceptional skill and mental retardation*. Hillsdale, NJ: Laurence Erlbaum.

Minagar, A., Ragheb, J., & Kelley, R. E. (2003). The Edwin Smith surgical papyrus: Description and analysis of the earliest case of aphasia. *Journal of Medical Biography, 11*(2), 114-117.

Miyazaki, K. (1988). Musical pitch identification by absolute pitch possessors. *Perception & Psychophysics, 44*(6), 501-512.

Moss, H. (2003). Implicit selves: A review of the conference. In J. LeDoux, J. Debiec & H. Moss (Eds.), *The self: From soul to brain* (Vol. 1001, pp. 1-30). New York: The New York Academy of Sciences.

Nelson, C., & Bloom, F. (1997). Child development and neuroscience. *Child Development, 68*(5), 970-987.

Nettle, D. (2005). *Happiness: The science behind your smile*. Oxford: Oxford University Press.

Nettle, D., & Berns, G. (2005). Satisfaction and happiness. On *Science Friday* [Radio broadcast: 9/9/05]. New York: NPR.

Norton, A., Winner, E., Cronin, K., Overy, K., Lee, D. J., & Schlaug, G. (2005). Are there pre-existing neural, cognitive, or motoric markers for musical ability? *Brain Cognition, 59*(2), 124-134.

Oerter, R. (2003). Biological and psychological correlates of exceptional performance in development. *Annals of the New York Academy of Science, 999*, 451-460.

Orsmond, G. I., & Miller, L. K. (1999). Cognitive, musical and environmental correlates of early music instruction. *Psychology of Music, 27*, 18-37.

Overman, A. A., Hoge, J., Dale, J. A., Cross, J. D., & Chien, A. (2003). EEG alpha desynchronization in musicians and nonmusicians in response to changes in melody, tempo, and key in classical music. *Perceptual Motor Skills, 97*(2), 519-532.

Panksepp, J., & Bekkedal, M. Y. V. (1997). The affective cerebral consequence of music: Happy vs sad effects on the EEG and clinical implications. *International Journal of Arts Medicine, 5*(1), 18-27.

Pantev, C., Engelien, A., Candia, V., & Elbert, T. (2001). Representational cortex in musicians. Plastic alterations in response to musical practice. *Annals of the New York Academy of Science, 930*, 300-314.

Parsons, L. M. (2000). *Functional anatomy of pitch, rhythm, melody, and harmony.* Paper presented at the Mapping music in the brain: A satellite symposium of the annual conference for human brain mapping, San Antonio, Texas.

Parsons, L. M. (2001). Exploring the functional neuroanatomy of music performance, perception, and comprehension. *Annals of the New York Academy of Science, 930*, 211-231.

Parsons, L. M., & Fox, P. (1997). Sensory and cognitive tasks: The cerebellum and cognition. In J. D. Schmahmann (Ed.), *International review of neurobiology, cerebellum and cognitio*. San Diego: Academic Press.

Parsons, L. M., Sergent, J., Hodges, D. A., & Fox, P. T. (2005). The brain basis of piano performance. *Neuropsychologia, 43*(2), 199-215.

Pascual-Leone, A., Nguyet, D., Cohen, L. G., Brasil-Neto, J. P., Cammarota, A., & Hallett, M. (1995). Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. *Journal of Neurophysiology, 74*(3), 1037-1045.

Patel, A. D. (2003). Language, music, syntax and the brain. *Nature Neuroscience, 6*(7), 674-681.

Patel, A. D., Peretz, I., Tramo, M., & Labreque, R. (1998). Processing prosodic and musical patterns: A neuropsychological investigation. *Brain and Language, 61*(1), 123-144.

Penhune, V. B., Zatorre, R. J., & Evans, A. (1998). Cerebellar contributions to motor timing: A PET sutdy of auditory and visual rhythm reproduction. *Journal of Cognitive Neuroscience, 10*, 752-765.

Penhune, V. B., Zatorre, R. J., & Feindel, W. (1999). The role of auditory cortex in retention of rhythmic patterns as studied in patients with temporal lobe removals including Heschl's gyrus. *Neuropsychologia, 37*(3), 315-331.

Pepper, T. (2005, February 21). Inside the head of an applicant. *Newsweek, CXLV*.

Peretz, I. (2006). The nature of music from a biological perspective. *Cognition, 100*(1), 1-32.

Peretz, I., Ayotte, J., Zatorre, R. J., Mehler, J., Ahad, P., Penhune, V. B., et al. (2002). Congenital amusia: A disorder of fine-grained pitch discrimination. *Neuron, 33*(2), 185-191.

Peretz, I., Blood, A. J., Penhune, V. B., & Zatorre, R. J. (2001). Cortical deafness to dissonance. *Brain, 124*(Pt 5), 928-940.

Peretz, I., & Cotheart, M. (2003). Modularity of music processing. *Nature Neuroscience, 6*, 688-691.

Peretz, I., & Morais, J. (1980). Modes of processing melodies and ear asymmetry in nonmusicians. *Neuropsychologia, 18*, 477-489.

Peretz, I., & Morais, J. (1989). Music and modularity. *Contemporary Music Review, 4*, 277-291.

Peretz, I., & Zatorre, R. J. (2003). *The cognitive neuroscience of music*. Oxford: Oxford University Press.

Peretz, I., & Zatorre, R. J. (2005). Brain organization for music processing. *Annual Review of Psychology, 56*, 89-114.

Piaget, J. (1950). *The psychology of intelligence*. London: Routledge and Kegan Paul.

Pinker, S. (1997). *How the mind works*. New York: W. W. Norton & Company, Inc.

Platel, H., Baron, J. C., Desgranges, B., Bernard, F., & Eustache, F. (2003). Semantic and episodic memory of music are subserved by distinct neural networks. *Neuroimage, 20*(1), 244-256.

Platel, H., Price, C., Baron, J. C., Wise, R., Lambert, J., Frackowiak, R. S., et al. (1997). The structural components of music perception. A functional anatomical study. *Brain, 120 ( Pt 2)*, 229-243.

Popescu, M., Otsuka, A., & Ioannides, A. A. (2004). Dynamics of brain activity in motor and frontal cortical areas during music listening: a magnetoencephalographic study. *Neuroimage, 21*(4), 1622-1638.

Posner, M., & Raichle, M. (1994). *Images of mind*. New York: Scientific American Library.

Price, H. E. (1999). Forum. *Journal of Research in Music Education, 47*(3), 196-197.

Ramachandran, V., & Blakeslee, S. (1998). *Phantoms in the brain: Probing the mysteries of the human mind*. New York: HarperCollins.

Ratey, J. (2001). *A user's guide to the brain*. New York: Vintage Books.

Rauscher, F. H., Shaw, G. L., & Ky, K. N. (1993). Music and spatial task performance. *Nature, 365*, 611.

Reimer, B. (1989). *A philosophy of music education* (2 ed.). Englewood Cliffs, NJ: Prentice-Hall.

Restak, R. (1994). *The modular brain*. New York: Scribner.

Roberts, L. (1989). Are neural nets like the human brain? *Science, 243*(4890), 481-482.

Roederer, J. (1982). Physical and neuropsychological foundations of music: The basic questions. In M. Clynes (Ed.), *Music, mind, and brain: The neuropsychology of music*. New York: Plenum Press.

Rolls, E. (1989). The representation and storage of information in neuronal networks in the primate cerebral cortex and hippocampus. In R. Durbin, C. Miall & G. Mitchison (Eds.), *The computing neuron*. New York: Addison-Wesley.

Rosenthal, R. K. (1984). The relative effects of guided model, model only, guide only, and practice only treatments on the accuracy of advanced instrumentalists' musical performance. *Journal of Research in Music Education, 32*, 265-274.

Ross, D. A., Olson, I. R., & Gore, J. C. (2003). Cortical plasticity in an early blind musician: An fMRl study. *Magnetic Resonance Imaging, 21*(7), 821-828.

Saffran, J. R. (2003). Musical learning and language development. *Annals of the New York Academy of Science, 999*, 397-401.

Sakai, K., Hikosaka, O., Miyauchi, S., Takino, R., Tamada, T., Iwata, N. K., et al. (1999). Neural representation of a rhythm depends on its interval ratio. *Journal of Neuroscience, 19*(22), 10074-10081.

Sang, R. C. (1987). A study of the relationship between instrumental music teachers' modeling skills and pupil performance behaviors. *Bulletin of the Council for Research in Music Education, 43*, 313-329.

Satoh, M., Takeda, K., Nagata, K., Hatazawa, J., & Kuzuhara, S. (2003). The anterior portion of the bilateral temporal lobes participates in music perception: a positron emission tomography study. *AJNR. American Journal of Neuroradiology, 24*(9), 1843-1848.

Schlaug, G. (2001). The brain of musicians: A model for functional and structural changes. *Annals of the New York Academy of Science, 930*, 281-299.

Schlaug, G., Jäncke, L., Huang, Y., Staiger, J., & Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia, 33*, 1047-1055.

Schlaug, G., Jäncke, L., Huang, Y., & Steinmetz, H. (1994). *In vivo morphometry of interhemispheric asymmetry and connectivity in musicians.* Paper presented at the 3rd international conference for music perception and cognition, Liege, Belgium.

Schlaug, G., Jäncke, L., Huang, Y., & Steinmetz, H. (1995). In vivo evidence of structural brain asymmetry in musicians. *Science, 267*(5198), 699-701.

Schlaug, G., Norton, A., Overy, K., & Winner, E. (2005). Effects of music training on the child's brain and cognitive development. *Annals of the New York Academy of Science, 1060*, 219-230.

Schmidt, L. A., & Trainor, L. J. (2001). Frontal brain electrical activity (EEG) distinguishes valence and intensity of musical emotions. *Cognition & Emotion, 15*(4), 487-500.

Schmithorst, V. J., & Holland, S. K. (2004). The effect of musical training on the neural correlates of math processing: a functional magnetic resonance imaging study in humans. *Neuroscience Letters, 354*(3), 193-196.

Schneider, P., Sluming, V., Roberts, N., Scherg, M., Goebel, R., Specht, H. J., et al. (2005). Structural and functional asymmetry of lateral Heschl's gyrus reflects pitch perception preference. *Nature Neuroscience, 8*(9), 1241-1247.

Schon, D., Magne, C., & Besson, M. (2004). The music of speech: Music training facilitates pitch processing in both music and language. *Psychophysiology, 41*(3), 341-349.

Selby, B., Rosenfeld, J., Styles, E., & Westcott, J. (1982). Which hemisphere is trained? The need for a new strategy for interpreting hemispheric asymmetries in music perception. *Psychology of Music, special issue*, 101-103.

Sergent, J. (1993). Mapping the musician brain. *Human Brain Mapping, 1*(1), 20-38.

Seung, Y., Kyong, J. S., Woo, S. H., Lee, B. T., & Lee, K. M. (2005). Brain activation during music listening in individuals with or without prior music training. *Neuroscience Research, 52*(4), 323-329.

Shahin, A., Bosnyak, D. J., Trainor, L. J., & Roberts, L. E. (2003). Enhancement of neuroplastic P2 and N1c auditory evoked potentials in musicians. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 23*(13), 5545-5552.

Shallice, T. (2003). Functional imaging and neuropsychology findings: How can they be linked? *Neuroimage, 20*, 146-154.

Shaw, G. L. (2000). *Keeping Mozart in mind*. San Diego: Academic Press.

Shepherd, G. (1990). *The synaptic organization of the brain* (3 ed.). New York: Oxford.

Shepherd, G. (1994). *Neurobiology*. New York: Oxford University Press.

Slone, K. C. (1985). *They're rarely too young and never too old "To Twinkle"*. Ann Arbor: Shar Products Company.

Sluming, V., Barrick, T., Howard, M., Cezayirli, E., Mayes, A., & Roberts, N. (2002). Voxel-based morphometry reveals increased gray matter density in Broca's area in male symphony orchestra musicians. *Neuroimage, 17*(3), 1613-1622.

Spintge, R., & Droh, R. (1992). *MusicMedicine* (Vol. 1). St. Louis, MO: MMB Music.

Stafford, T., & Webb, M. (2005). *Mind hacks: Tips and tools for using your brain*. Cambridge: O'Reilly.

Steele, K. M., Brown, J. D., & Stoecker, J. A. (1999). Failure to confirm the Rauscher and Shaw description of recovery of the Mozart effect. *Perceptual and Motor Skills, 88*(3 Pt 1), 843-848.

Stephens, G. L., & Graham, G. (2000). *When self-consciousness breaks*. Cambridge, MA: MIT Press.

Stiles, J. (2000). Neural plasticity and cognitive development. *Developmental Neuropsychology, 18*(2), 237-272.

Stillings, N., Weisler, S., Chase, C., Feinstein, M., Garfield, J., & Rissland., E. (1995). *Cognitive science: An introduction* (2 ed.). Cambridge, MA: Bradford.

Sutoo, D., & Akiyama, K. (2004). Music improves dopaminergic neurotransmission: demonstration based on the effect of music on blood pressure regulation. *Brain Research, 1016*(2), 255-262.

Sylwester, R. (1995). *A celebration of neurons: An educator's guide to the human brain*. Alexandria, VA: Association for Supervision and curriculum Development.

Takeuchi, A., & Hulse, S. (1993). Absolute pitch. *Psychological Bulletin, 113*, 345-361.

Tanioka, F., Takazawa, T., Kamata, S., Kudo, M., Matsuki, A., & Oyama, T. (1987). Hormonal effect of anxiolytic music in patients during surgical operations under epidural anesthesia. In R. Spintge & R. Droh (Eds.), *Music in medicine*. Berlin: Springer-Verlag.

Tervaniemi, M., Medvedev, S. V., Alho, K., Pakhomov, S. V., Roudas, M. S., Van Zuijen, T. L., et al. (2000). Lateralized automatic auditory processing of phonetic versus musical information: a PET study. *Hum Brain Mapp, 10*(2), 74-79.

Thivard, L., Belin, P., Zibovicius, M., Poline, J., & Samson, Y. (2000). A cortical region sensitive to auditory spectral motion. *NeuroReport, 11*, 2969-2972.

Trainor, L. J., Shahin, A., & Roberts, L. E. (2003). Effects of musical training on the auditory cortex in children. *Annals of the New York Academy of Science, 999*, 506-513.

Tsao, C. C., Gordon, T. F., Maranto, C. D., Lerman, C., & Murasko, D. (1991). The effects of music and directed biological imagery on immune response S-IgA. In M. C. D. (Ed.), *Applications of music in medicine*. Washington, D. C.: National Association for Music Therapy.

Tzourio, N., Nkanga-Ngila, B., & Mazoyer, B. (1998). Left planum temporale surface correlates with functional dominance during story listening. *NeuroReport, 9*, 829-833.

Vaughn, K. (2000). Music and mathematics: Modest support for the oft-claimed relationship. *Journal of Aesthetic Education, 34*(3-4), 149-166.

Vollmer-Haase, J., Finke, K., Hartje, W., & Bulla-Hellwig, M. (1998). Hemispheric dominance in the processing of J.S. Bach fugues: a transcranial Doppler sonography (TCD) study with musicians. *Neuropsychologia, 36*(9), 857-867.

Vuust, P., Pallesen, K. J., Bailey, C., van Zuijen, T. L., Gjedde, A., Roepstorff, A., et al. (2005). To musicians, the message is in the meter pre-attentive neuronal responses to incongruent rhythm are left-lateralized in musicians. *Neuroimage, 24*(2), 560-564.

Wagner, M., & Hannon, R. (1981). The effect of music listening and attentiveness training on the EEG's of musicians and nonmusicians. *Journal of Music Therapy, 14*, 151-164.

Wallin, N. L., Merker, B., & Brown, S. (2000). *The origins of music*. Cambridge, MA: MIT Press.

Ward, W. (1999). Absolute pitch. In D. Deutsch (Ed.), *The psychology of music* (2nd ed.). New York: Academic.

Warrier, C. M., & Zatorre, R. J. (2004). Right temporal cortex is critical for utilization of melodic contextual cues in a pitch constancy task. *Brain, 127*(Pt 7), 1616-1625.

Wilson, F. (1986). *Tone deaf and all thumbs*. New York: Viking.

Wilson, S. J., Pressing, J. L., & Wales, R. J. (2002). Modeling rhythmic function in a musician post-stroke. *Neuropsychologia, 40*(8), 1494-1505.

Yoo, S., Lee, C., & Choi, B. (2001). Human brain mapping of auditory imagery; event-related functional MRI study. *NeuroReport, 12*, 3045-3049.

Zatorre, R. J. (2003). Music and the brain. *Annals of the New York Academy of Science, 999*, 4-14.

Zatorre, R. J., & Belin, P. (2001). Spectral and temporal processing in human auditory cortex. *Cerebral Cortex, 11*(10), 946-953.

Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: Music and speech. *Trends in Cognitive Sciences, 6*(1), 37-46.

Zatorre, R. J., Halpern, A. R., Perry, D., Meyer, E., & Evans, A. (1996). Hearing in the mind's ear: A PET investigation of musical imagery and perception. *Journal of Cognitive Neuroscience, 8*(1), 29-46.

Zatorre, R. J., & McGill, J. (2005). Music, the food of neuroscience? *Nature, 434*(7031), 312-315.

Zatorre, R. J., & Samson, S. (1991). Role of the right temporal neocortex in retention of pitch in auditory short-term memory. *Brain, 114*(Pt. 6), 2403-2417.